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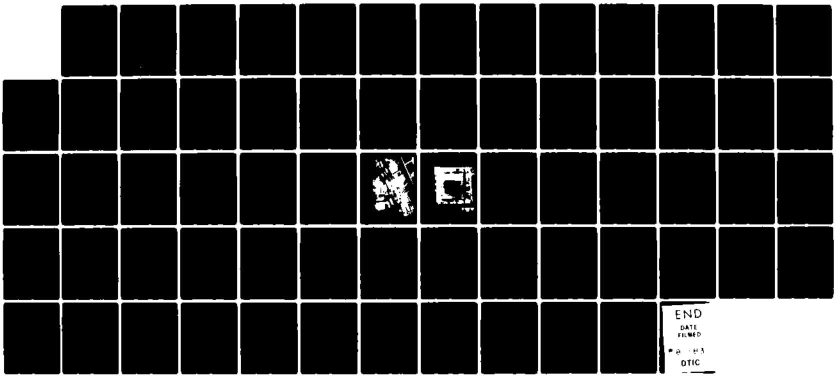

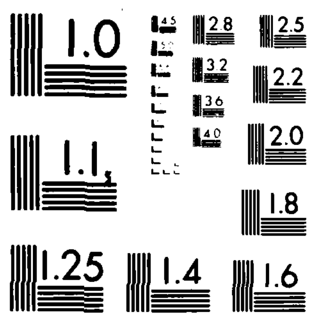

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LOW TEMPERATURE BEHAVIOR OF FUELS IN SIMULATED AIRCRAFT TANKS

May 1983

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LOW TEMPERATURE BEHAVIOR OF FUELS IN SIMULATED AIRCRAFT TANKS

(CRC PROJECT No. CA-58-78)

Prepared by the

CRC Aviation Group on Low Temperature
Flow Performance of Aviation Turbine Fuels

May 1983

Aviation Fuel, Lubricant, and Equipment Research Committee

of the

Coordinating Research Council, Inc.

TABLE OF CONTENTS

Page

TEXT

TABLE OF CONTENTS *(Continued)*

Page

TABLES

FIGURES

APPENDICES

I. SUMMARY

Lockheed and Boeing each made a series of tests in aircraft fuel tank simulators to provide an improved understanding of the flowability and pumpability of jet fuels at or below their freezing point where waxy components separate. Each simulator represented a section of an aircraft wing fuel tank. Tests simulated the low temperature cruise environment associated with long duration flights under extreme, high-altitude conditions. Holdup, the fraction of unavailable fuel remaining in the tank after attempted fuel withdrawal, was used to characterize pumpability after low temperature exposure.

The test fuels were derived from widely differing crude sources and were selected to cover a range of freezing points. Two of the test fuels were common to the Boeing and Lockheed investigations in order to assess variability due to simulator construction. One fuel in the Lockheed program contained a flow improver additive. In the Boeing program, one fuel was a blend of JP-5 and 9% marine diesel fuel.

The Lockheed and Boeing simulators produced generally similar results when tested over a range of tank skin temperatures, fuel discharge temperatures, and tank agitation modes (slosh, vibration, quiescent). From these results, a model was developed to predict holdup. The approximate average of a fuel's freezing point and pour point was found to correlate well with holdup tendencies in fuel tanks exposed to low temperatures.

This report on the low temperature behavior of aviation turbine fuels: (1) Reviews the findings of the Boeing and Lockheed simulator investigations, (2) Develops a useful correlation between laboratory tests on fuels and their performance in simulator tests, (3) Discusses the low temperature fuel properties that assure satisfactory aircraft operation, and (4) Recommends additional work needed to develop better models to predict low temperature behavior of fuels in operating aircraft.

II. BACKGROUND

The jet fuel supply crisis of 1973/74 accelerated interest in the low temperature properties of aircraft fuels because the freezing point specification test appeared to be a possible limitation in expanding availability. Fuel freezing point is defined as the temperature at which wax crystals melt and disappear upon reheating after fuel has been cooled to the point where wax crystals appear. The test measures the upper limit of a temperature band in which solid and liquid phases co-exist and some flow can occur. Freezing behavior of fuels used for long-range flights of several hours duration is of primary concern. Prolonged operations in the low temperatures of cruising altitudes can permit fuel to chill to a point where phase separation begins. The fuel would not cool to ambient temperature, but, due to aerodynamic heating effects, would approach the recovery temperature. Recovery temperature is above ambient by about 90% of the ram temperature rise calculated at the aircraft Mach number. For example, at a 37,000 foot standard day, Mach 0.8 cruise condition, ambient temperature would be -56.6°C (-69.7°F) and recovery temperature would be 25°C (45°F) higher or -31.6°C (-24.7°F).

ASTM's Technical Division J on Aviation Fuels conducted a survey of the aviation and petroleum industries on raising the freezing point of Jet A-1, the fuel used internationally, and then staged a December 1976 Symposium on Jet Fuel Low Temperature Requirements (Reference 1). This activity led to a relaxation of both ASTM's D1655 Specification and IATA's Guidance Material for Jet A-1 from -50°C to -47°C maximum freezing point in order to improve availability.

Looking beyond the present to the availability limitations of future fuels, NASA's Lewis Research Center held a workshop on jet aircraft hydrocarbon fuels technology in 1977 (Reference 2). One of the recommendations of that workshop was to experimentally investigate the fuel freezing behavior in a fuel tank to determine if two-phase flow could be tolerated.

Subsequently, NASA let a contract to the Lockheed California Company to study the cold flow behavior of fuels in a simulated aircraft wing tank. NASA also requested the CRC group on Low Temperature Flow Properties of Aviation Turbine Fuels to recommend fuels to be used in the Lockheed study. The CRC group recommended and supplied test fuels selected from paraffinic and naphthenic crude sources. The CRC conducted a variety of laboratory tests on these fuels in addition to determining their freeze points using the specification method. Various chemical and physical properties of the fuels were determined. The fuels were subjected to additional tests using methods which might be used to describe low temperature handling characteristics. Results of the CRC tests were appended to the Lockheed report (Reference 2). Analyses and comments on the Lockheed test data were reported in Reference 3.

After completion of the Lockheed program, the Air Force requested CRC to carry out a follow-on program. The principal objective was an improved understanding of flowability and pumpability of jet fuels at or near their freezing point. Additionally, there was the question as to whether or not the Lockheed findings could be confirmed in a different wing tank simulator. The CRC subcontracted with the Boeing Aerospace Company to conduct wing tank simulator tests for this ongoing program. Results of the Boeing study are included in this report.

III. LOCKHEED AND BOEING TEST PROGRAMS

The following sections provide brief descriptions of the simulator tanks, of the test procedures, and of the test fuels used by Boeing and Lockheed. Complete descriptions of the Lockheed program are given in Reference 3. Differences in construction, procedure, or fuels that might influence results are discussed throughout this report.

A. DESCRIPTION OF SIMULATOR TANKS

The internal configuration of the Boeing test tank was designed to simulate a portion of an outer wing fuel tank of a modern commercial jet aircraft. Aircraft aluminum (6061-T6), at thicknesses representative of a B-747 outboard main tank, was used throughout providing realistic thermal conductivity rates through the structure. Standard aircraft anticorrosion coating was applied to the interior bottom surface to the height of the lower stringers. The internal dimensions of the tank were 51 cm high, 51 cm wide, and 76 cm long, resulting in a volume of 198 liters. Modeling of important vertical dimensions of the inboard section of the B-747 outboard main tank was full scale. The tank was designed to permit simulation of atmospheric pressure up to 40,000 ft. An interior view of the Boeing test tank is shown in Figure 1.

The Lockheed test tank was also designed to simulate a portion of an outer wing fuel tank of a modern commercial jet aircraft. Interior dimensions of the tank are 50.8 cm (20 in.) high, 50.8 cm (20 in.) wide, and 76.2 cm (30 in.) long for a resulting volume of 196 liters. An interior view of the Lockheed test tank is shown in Figure 2. The tank was tilted 4° to the horizontal with the boost pump outlet and the drain holes on the low side.

While the interior dimensions of the Boeing and Lockheed test tanks were similar, the construction and arrangement differed in certain respects. These differences could affect heat transfer rates. For example, the Boeing tank contained two stringers, fabricated from two angle sections 7.6 cm high while the Lockheed tank contained three one-piece stringers, each 5.7 cm high. The Boeing tank contained a fuel boost pump, suction plumbing, vapor separation plumbing, and the pump discharge plumbing. The Lockheed tank contained two small ejectors, the related small size plumbing, and a perforated recirculation manifold. The Lockheed tank discharged through an opening in the bottom, which led to an external fuel boost pump.

Each test tank had viewing ports, cooling panels on the upper and lower surfaces, and insulation on the other surfaces to assure that heat transfer was confined to the upper and lower surfaces. There were provisions for simulating sloshing and vibration. Thermocouples were used to sense temperature inside the tank. These were mounted on vertical racks and spaced to provide a temperature profile of the fuel. Thermocouples were also provided on the upper and lower outer skins.

B. TEST PROCEDURES

Lockheed and Boeing used similar basic test procedures. The simulator tank was filled with test fuel, usually such that fuel wetted the upper surface. Upper and lower skins were chilled to a pre-selected temperature, while fuel temperature profiles were monitored and recorded. For most test modes, skin temperature was held essentially constant for the time needed to reach a target temperature in the fuel 2.5 cm above the tank bottom, at which time withdrawal was begun. In some tests, skin temperatures and withdrawal were programmed according to a time schedule. Lockheed withdrew fuel by operating ejectors and an external boost pump. Boeing withdrew fuel in three successive stages: 1) level gravity drain, 2) tilted gravity drain, and 3) internal boost pump. Holdup was measured by weighing removed fuel and calculating percent of fuel trapped in the simulator. After each test, trapped fuel was melted and drained out, and fuel fractions were recombined for the next run.

Lockheed conducted various types of low temperature tests in its simulator tank. All tests were conducted by filling the test tank with fuel at ambient temperature, about 20°C, and then chilling it through the upper and lower skins according to a flight mission temperature profile. Test periods ranged from 5 to 300 minutes under simulated cruise conditions and with the lowest expected skin temperatures.

The tests applicable to this program are summarized in Table I, and the test modes are as follows:

1. Static - Fuel quiescent until end of test.
2. Recirculation - Gravity flow to boost pump and pumped back to opposite end of tank at 6 liters per minute.
3. Sloshing - Tank oscillated throughout test.
4. Divider - Static test with a divider plate installed to represent a baffle within the tank.
5. Ejector - Special recirculation (two tests).
6. Dry Fuel - Nitrogen dried to remove dissolved water.
7. Scheduled Withdrawal - Several tests where skin temperature and fuel withdrawal were varied.

Boeing conducted tests under static, slosh, and vibration conditions as summarized in Table II.

To speed up collection of test data, Boeing prechilled the bulk fuel to a temperature about 10°C above the fuel freezing point before filling the test tank and then started the simulated low temperature cruise cycle by further chilling the fuel through the upper and lower skins. Test duration was then determined by the temperature of the probe located 2.54 cm above the bottom skin. Durations ranged from 5 to 274 minutes.

[illegible]. TEST FUELS

Lockheed tested the first 12 fuels shown in Table III. Fuels originally in the Lockheed program are identified by codes starting with L- or LFP-. The fuels were selected from widely different petroleum crude sources and with a range of freezing points. One fuel (L-7) had a flow improver additive. These additives change the structure of solidifying fuel from one with extensive cross-linking of modules, which inhibits flow, to one with more discrete agglomerations of molecules which can move relative to one another.

Boeing tested five fuels, LFP-1, LFP-8, B-3, B-4 and B-5. Boeing fuels B-3 and B-5 were JP-8 fuels from shale and petroleum, respectively. The freezing point for B-5 was slightly off specification. Fuel B-4, a blend of JP-5 and marine diesel fuel, represents a possible means for extending the supply of U.S. Navy jet fuel.

A variety of laboratory tests of fuel low temperature properties was conducted on most of the fuels. The test methods used are described in Appendix C and are referred to as appropriate throughout this report.

IV. DISCUSSION

This discussion is divided into three sections, whose objectives are:

- To review the findings of the Boeing and Lockheed simulation investigations.
- To point out what needs to be done in subsequent programs.
- To examine the least restrictive low temperature fuel property that assures satisfactory aircraft operation.

A. REVIEW OF FINDINGS OF SIMULATOR PROGRAMS

Holdup, as measured in a simulator, represents the separated wax plus entrapped liquid at the end of a particular time-temperature test. Since the wax forms first on cold surfaces such as tank skins or stringers, it is apt to remain there until it melts. If the wax that separates also plugs filters or lines, it could interrupt fuel flow to an engine.

During the test cycle, there is usually a large temperature difference between the chilled tank surface and the bulk fuel as shown by typical data in Figure 3. This characteristic thermal gradient in the simulators reflects the low thermal conductivity of fuel and the dominating role of conduction in heat transfer to the tank upper and lower skins. The result is a highly nonequilibrium and dynamic system that may (or may not) undergo phase change in the zone next to the skins, depending on the properties of the fuels.

In a typical aircraft flight, the sharp thermal gradient within the tank would undergo rapid change as an aircraft descended to warmer flight altitudes. Some or all of the holdup fuel would be expected to become a usable liquid on descent. It is impossible to prescribe an "acceptable" level of holdup prior to descent because the tolerance of a system depends on a particular tank design and system configuration. Instead, the findings of these simulator tests provide a data source for designers in the form of a fuel criterion such as freezing point and pour point in a relationship to holdup at the end of high altitude cruise.

Aircraft design parameters other than those represented in the tests by Lockheed and Boeing need consideration and are discussed in Appendix A.

1. Effects of Slosh and Vibration

The three temperature profiles plotted in Figure 3 are those exhibited at the initiation of fuel withdrawal for three Boeing tests with paraffinic LFP-1 fuel under static, slosh, and vibration conditions. All these tests had the same target or control temperature at 2.5 cm above the tank bottom. The profiles show a broad, uniform temperature mixing region at the center and a steep conductive heat transfer controlled zone between this region and the chilled bottom skin. A very narrow convective heat transfer controlled region

exists at the top surface, but it is imprecisely defined because of the wide thermocouple spacing. These temperature profiles are typical of those measured for all the Boeing tests, and they are similar to those reported for previous Boeing in-house tests and for at least the low holdup tests in the Lockheed studies. The effect of the tank agitation is to increase mixing and heat transfer, reducing the uniform center temperature. The agitation increases in intensity from sloshing to vibration; the combined sloshing and vibration mode (not shown in Figure 3) yields temperature profiles nearly equivalent to those produced by vibration alone. These results depicted in the figure are typical of those obtained with paraffinic and naphthenic Jet A. The effect of agitation is less pronounced with the other three fuels tested by Boeing.

In the Boeing tests, target temperatures for initiation of fuel withdrawal, measured 2.5 cm above the bottom skins, were varied from 2.8°C above the freezing point to 5.6°C below the freezing point. Figure 3 represents tests at a target temperature equal to the freezing point (-41°C) for Jet A paraffinic fuel (LFP-1). Only the bottom 2.5 cm fuel layer and a very thin layer at the top surface (comprising about 5% of the total tank volume) were below the freezing point. Since the boundary layer temperatures within these zones do not vary appreciably at a given target temperature, there is no large difference between holdup measurements for quiescent, sloshing, vibrating, or a combined sloshing/vibrating environment. Measured holdups ranged from 2.8% to 3.3% of total tank volume. Similar results were observed in the Lockheed tests with slosh and vibration.

2. Correlation of Data

Most of the holdup tests conducted by Boeing and Lockheed were made with the simulator tank full, i.e., with fuel in contact with the upper skin surface. 110 tests of this type were made, 65 by Lockheed and 45 by Boeing. Table IV summarizes pertinent data for these 110 tests.

In the Lockheed tests, fuel was pumped out and weighed with the tank in the original position, 4° to the horizontal. The quantity which did not flow by gravity and ejector pump to the boost pump constituted the holdup.

In the Boeing tests, three measurements were made for holdup: first with a level tank and gravity drain, second by tilting the tank 14 degrees to the horizontal, and last with boost pump ON. Holdup data reported in Table IV for Boeing tests are for boost pump ON which is similar to the Lockheed procedure.

In the Lockheed tests, the initial fuel temperature in the simulator was near ambient (20-30°C), while Boeing pre-chilled the bulk fuel to about 10°C above its freezing point before filling the simulator. Despite these differences in test procedure, it is possible to compare the holdup data between the Lockheed and Boeing simulators because the selection of an appropriate bulk temperature thermocouple compensates for the greater time required in the Lockheed test procedure to reach the same bulk temperature. Figure 3 illustrates the fact that the bulk fuel temperature at the start of fuel withdrawal after a period

of chilling through the skin is reasonably uniform between 10 and 40 cm above the skin and that a thermocouple reading selected in this zone is representative of a midtank temperature.

A tank fuel temperature profile is shown schematically in Figure 4 for a given tank skin temperature (TS) and a midtank temperature (TM). These two temperatures (TS and TM) can be used to identify a temperature profile. There is a temperature for any fuel below which it does not exhibit significant flowability for recovering fuel from the simulated aircraft wing fuel tanks. This temperature is defined here as that fuel's solidification index (SI). If a fuel's SI is less than or equal to TS, then the holdup should be zero since none of the fuel is at a temperature below its SI. If, on the other hand, the fuel's SI equals or exceeds TM, the holdup would be 100%. Other fuels with SI's between TS and TM would produce intermediate holdups, depending on their relative relationship to TS and TM. Thus the percent holdup (HU) should be related to the following function:

$$HU = f\left(\frac{SI-TS}{TM-TS}\right)$$

The freeze point (FP) of a fuel defined by ASTM D 2386 and the pour point (PP) defined by ASTM D 97 can be considered as the onset of wax separation and a special case of solidification, respectively (see Appendix C for description of test methods). These two laboratory tests can be used to define the SI of a fuel as it is related to holdup in an aircraft tank at low temperature, e.g., SI = a FP + b PP, all in °C.

A linear regression of the Boeing and Lockheed data provided the following relationship between holdup and the ratio of (SI-TS)/(TM-TS):

$$HU = e^{\left[2.824\left(\frac{SI-TS}{TM-TS}\right) + 0.72\left(\frac{SI-TS}{TM-TS}\right)^{2}\right]} - 1$$

$$\text{where } SI = 0.5289\ PP^{(1)} + 0.484\ FP$$

The statistical correlation value, R^2, was 0.96 and the standard error of ln (HU +1) was 0.35. This means that 96% of the variability in ln (HU + 1) is explained by the model and that the estimated standard error of HU is 35%.

Table IV gives predicted values and the difference between observed and estimated values for each test. The large errors occur when the ratio (SI-TS)/(TM-TS) approaches a value of one.

Figure 5 compares observed and estimated holdup for all fuels with observed holdups below 30%. Figure 6 shows the difference between estimated and observed holdup for each of the test fuels. There are no test fuels which appear meaningfully biased. It appears, therefore, that the SI developed from the regression is a good predictor of low temperature fuel holdup.

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(1) There was a broad variation in the pour point data determined for the fuels used in the Lockheed and Boeing programs. The average of several PP determinations was used in the data correlation. This is greater PP precision than would normally be obtained.

The regression showed SI to be approximately equal to the average of the freeze and pour points. Using the definition for SI, the ratio (SI-TS)/(TM-TS) can be calculated. Figure 7 shows the excellent relationship between holdup and this parameter. When the ratio is = >1.0, i.e., SI=>TM, holdup is high, =>37%, and indeterminate.

Most of the holdup tests were conducted with the simulator tanks full and the fuel in contact with the upper tank surface. The holdup correlations were developed for this case. However, Lockheed noted that for holdups to about 6%, most of the solids were restricted to the lower skin and stringer surfaces of the tank. Therefore, the relationship might be applicable for partially filled tanks for low holdup conditions.

The prediction parameter (SI-TS)/(TM-TS) is highly sensitive to measurement errors because it is a ratio of two deltas. For example, assume a ratio of 12/18 = 0.667 which predicts an 8.06% holdup. If there were a 1°C measurement error in both numerator and denominator deltas, the ratio could be 11/19 = 0.579 which predicts a 5.53% holdup.

A number of different models were explored using the fuel temperature 1.3 cm from the bottom of the tank. None of those tried provided a satisfactory estimate of holdup, even when the analysis was restricted to low holdups below 12%.

No attempt was made to determine if testing mode, e.g., sloshing or vibration, had a significant effect on holdup that was not reflected by the change in the fuel TM.

As described above, the calculated solidification index, which is approximately halfway between fuel freezing point and pour point, gave a reasonable fit of the experimental holdup data. This is an initial correlation study, and should not be interpreted as concluding that the ultimate choice in low temperature flow properties is the solidification index, to the exclusion of all other properties. It was chosen for study in part because of intuitive fit and in part because freeze and pour data were abundantly available for all Lockheed and Boeing simulator fuels. It has the disadvantage of requiring two fuel tests, one of which, the pour point, is so imprecise as to be reportable only to the nearest 3°C. It was necessary to perform multiple replicate analyses on each test fuel to obtain precise freeze and pour point values for this study.

A variety of alternative low temperature bench tests was explored to characterize the Lockheed test fuels. Table V presents results of these test methods. The test methods are described in Appendix C. Many of these alternate tests indicate a low temperature operability limit in the temperature range where the fuel is a mixture of liquid fuel and wax crystals, a concept in general agreement with tank simulator observations. Although the primary purpose for development of these tests was the characterization of fuels containing flow improvers, the Lockheed fuels offered an opportunity to see whether any of the tests might offer a satisfactory relationship with performance in a wing tank simulator. Figure 8 shows a graphical comparison of these bench tests with the freeze-pour solidification index.

Unfortunately, results were available on only seven of the fifteen test fuels, only one of which was included in the Boeing program. Hence, their suitability for characterizing a fuel's low temperature behavior and holdup needs to be further evaluated.

There have been other attempts to correlate results of one or both of the simulator test data. These are described in Reference 4 and in Appendix B.

Flow improving additives have been considered as a means to decrease fuel holdup. These additives appear to be selective in their ability to effect low temperature flow improvement in various fuels. Flow improvers do not reduce the amount of wax formed, but change its character resulting in better flowability at low temperatures. Consequently, two tests, Lockheed Nos. 99 and 100, were made using flow improved fuel, L-7. The addition of flow improver depressed pour point by 13°C, compared with the base fuel, LFP-5. Holdup was reduced about 50% in test No. 99 relative to test No. 97. This flow improver was optimized for diesel fuels and was not optimized for the L-7 fuel. There was very limited testing of additives in these programs.

3. Procedural Effects on Test Results

Effect of Repeated Freezing and Reconstitution of Fuel Specimen - Early in the Boeing program, concern was expressed about the reliability of data generated by repeated freezing of a given batch of fuel. In determinations of the pour point (ASTM D97) of heavier fuels, such as diesel, it has been found that it was necessary to raise the temperature of the specimen to the greater of 46°C or 8°C above the pour point to completely reconstitute the fuel specimen. This need appears to arise because of the persistence of micro-crystals formed at low temperatures which may not be visible when the specimen temperature is raised only a few degrees above the pour point; these crystals can serve as condensation nuclei when the chilling cycle is repeated. This "hysteresis" effect has been shown to lead to variability in pour point (and possibly in other low temperature property) measurements if the temperature of the fuel is not raised well above the pour point between tests.

Fuels in the Boeing and Lockheed programs were repeatedly frozen and melted in each test series, which raised a question as to the validity of results. Further, there was essentially no repetition of the data points which might shed light on the issue. For cost reasons, it was proposed that resolution of the hysteresis concerns be carried out using a laboratory scale device; and the Shell Cold Flow test method was selected as suitable for the purpose. This test (IP 217/66 tentative) was proposed to determine the extent to which turbine fuels will gravity flow (slump) to an aircraft fuel tank pump inlet at low temperatures. Measurements are made primarily between the freezing point and pour point temperatures of the fuel and depend upon the yield value of the fuel/wax mixtures at any particular temperature. The apparatus (Figure 9) consists of two cylindrical chambers separated by a large poppet valve. Fuel is added to the upper chamber, the test apparatus and fuel are brought to the desired temperature and are then held for one hour to ensure isothermal fuel temperature. The valve separating the chambers is then opened for 10 seconds, allowing the fluid portion of the fuel to flow (slump)

into the lower chamber. The spring-loaded valve is then closed and the equipment warmed to ambient temperature. Unlike the actual aircraft application, the test fuel is not agitated; and all of the fuel and container reach an equilibrium temperature.

The Shell Cold Flow test procedure used by Boeing was to establish a holdup versus temperature curve using fresh specimens of fuel for each data point. After each test, the fuel was reconstituted by blending the portions of fuel in the upper and lower chambers of the test apparatus and then retested. Tests were conducted at or near a temperature which was experimentally determined to have a holdup near 30%.

The Shell Cold Flow tests were conducted with the five fuels employed in the Boeing program. Figures 10 through 14 show examples of the results obtained by this method. These data show no major differences in holdup between fresh fuel specimens and the reconstituted fuels. However, because of the high sensitivity of holdup with small changes in temperature, these results were inconclusive in establishing the existence of minor, but possibly significant, hysteresis effects.

Similar additional tests using the Shell Cold Flow procedure were conducted by the Fuels Branch of the USAF Wright Aeronautical Laboratories at Wright-Patterson Air Force Base. Two fuels were tested, LFP-1 and LFP-8, which are characteristic of paraffinic and naphthenic fuels, respectively. Their holdup data is summarized in Table VI, using recycled fuel rather than fresh fuel samples. The USAF data fall within 1°C of the Boeing data and show the same wide variation in holdup at a given temperature as the Boeing tests.

The variability among tests on fresh fuel specimens (repeatability) indicates that there are no statistically significant differences between fresh fuel test results. Accordingly, it was concluded that if there were a hysteresis effect, it was small and that the repeated freezing of reconstituted fuel specimens in the simulators would not contribute significantly to experimental error.

Upper and Lower Skin Temperature Control - At the start of the Boeing tests, the tank upper and lower surfaces (skin) were chilled to a predetermined temperature (usually 10°C below the freezing point) and held at that temperature as uniformly as possible throughout the remainder of the test. Significant skin temperature excursions above and below the target temperature affects the thermal profile in the tank, the rate of formation and matrix character of wax crystals, and, thus, the holdup results. The Boeing simulator utilized primary and secondary coolant heat exchangers to improve control; however, the manual control of the coolant flow presented problems in trying to hold within ±1°C of the skin temperature.

Chilldown Rate - Wax crystal growth and matrix formation during the freezing of jet fuels is believed to be dependent on cooling rate. Therefore, care was taken to provide consistent chilldown cycles for each test run; however, using manual control of the coolant flowing across the upper and lower surface of the tank allowed variation of chilldown rates.

Other Potential Errors in Holdup Measurement - The thermal simulator tanks, as in a typical airplane tank, had fuel transfer holes (some with flapper check valves) that could restrict gravity fuel flow if blocked by water-ice or other contaminants. The gravity drain system leading outside the test tanks was of a nominal 1.91 cm (0.75 in.) diameter, not typical of the size and length of airplane fuel tank installations. This condition of withdrawal was not real life, but was necessary for determination of gravity holdup. The blocking of the transfer holes and the drain system by non-fuel components could produce unreliable test results.

In the high holdup regime, the drain and transfer passages became blocked by dams of solidified fuel behind which liquid was trapped. Repeatability would have suffered due to the random blockage patterns formed by wax falling from the top and sides during withdrawal.

A possibly significant source of holdup measurement error in the tests is the time involved to stop the test when the target temperature is achieved and to accomplish: (1) level tank gravity drain, (2) tilted tank gravity drain, and (3) boost pump drain. These functions were operator controlled, with some nonuniformity in time depending on the amount of liquid drained, weighing system time constants, and other uncontrollable factors. During these activities, the coolant system continued to operate and would have frozen additional material in amounts which depended on time delays.

The significance of these various possible errors is unknown.

B. SUGGESTIONS FOR SUBSEQUENT PROGRAMS

Technology needs which should be developed as part of continuing efforts in the event that turbine-powered aircraft find it advantageous to use higher freezing point fuels are discussed in the following paragraphs.

1. Flight Temperature Analyses

The military has screened historical weather data for use in defining its operating temperature environments. These data are largely taken from the twice daily soundings of the atmosphere by weather stations. These data were treated statistically and were reduced to tables showing, by frequency of occurrence, the temperatures occurring at various altitudes. The most frequently occurring temperatures in various ranges were used to define "standard days" for specific applications. This work is published as MIL-STD-210B. The probability of occurrence of a given temperature level decreases with the degree of deviation from the norm. Temperature deviations representing a frequency of occurrence of so many days per year or of constant percentages of the time are shown in MIL-STD-210B.

Generally speaking, the cost of assuring equipment operation at a given temperature increases with that temperature's deviation from the norm. As a practical matter, a tolerable deviation from the norm of less severity than the absolute extremes can be selected for design and predicted operations as long as there are adequate safeguards in case the absolute extremes are encountered.

[illegible] one-day-per-year minimum atmospheric temperatures at cruise altitudes with reported minimum temperatures from commercial aviation experience indicates that the MIL-STD temperature extremes do not differ greatly from reported commercial temperatures. This comparison indicates that the minimum temperatures at cruise altitudes show enough similarity to reinforce the use of MIL-STD-210B at cruise altitudes. However, available data do not corroborate the MIL-STD values at other altitudes. Available data do not corroborate the MIL-STD frequency of occurrence data.

A further shortcoming of MIL-STD-210B and other atmospheric cold or arctic "day" standards is that no information is given on likely duration of temperatures either in persistence (time) or geographical extent. Analysis of aircraft tank fuel temperature variation during a flight requires a profile of temperatures along the route of flight on the day in question to be of practical use.

Areas of very low temperature are thought to occur in localized areas of a few hundred miles breadth. The specific dimensions of these areas are currently undefined. Various aircraft will encounter these low temperature areas in different ways. A tanker airplane used for inflight refueling may have to loiter in a specific area for a while, for example, to refuel fighter aircraft returning from a mission. Commercial flights or military transport flights will pass through these areas of unusually low air temperatures on only a part of their mission with the balance of the mission in more normal air temperature.

A well documented and broadly accepted single flight atmospheric model into which any aircraft can be placed for analysis is needed. The model could simply be a three-dimensional array of static air temperatures covering the areas of the earth's atmosphere where flights are considered.

There have been cursory attempts to define three-dimensional models. One model has been used in the work monitored by CRC. However, none of these models have been developed to the point of being established as a standard for design. Such a design standard is needed. A standard model would allow analyses of fuel temperatures on particular aircraft to be made that would consider time variations. It would also establish a standard for design and test of systems.

2. Computational Techniques Needed

Once a model atmosphere is stipulated, a method is required to compute the time varying thermal profile in the fuel tanks. This method should be sensitive to fuel level, since it is known that the fuel rate of cooling is greater when both upper and lower tank skins are wetted, the situation which exists in some fuel compartments early in the flight. At later times as the fuel level drops, contact between the fuel and the upper skin is lost; and the cooling rate decreases. On examination of the profile, it may then be possible to estimate the holdup fraction as a function of a postulated fuel freezing point, or solidification index, or on the basis of data from other laboratory devices.

B. Experimental Investigations

The release of frozen fuel from aircraft structures in the presence of wing bending or on descent to warmer environments may present a problem to engine fuel feed systems. The movement of pieces of frozen fuel may plug ejector pumps or clog screens at the entrance to fuel boost pumps. If these devices pass small pieces of frozen fuel, downstream fine mesh filters could be clogged. Such filters are often protected by heating devices to melt water ice particles, but may be ineffective in eliminating frozen fuel.

An experimental investigation into these problem areas would provide the basis for general guidelines which could be used to set acceptable holdup which would not affect total availability of fuel.

The use of fuel tank simulators to study low temperature behavior of fuel is expensive and time consuming. It would be desirable to develop a small-scale laboratory device to replace these simulators, especially for studies of the effects of fuel properties on holdup.

C. DEFINITION OF LOW TEMPERATURE FUEL PROPERTIES

Freezing point, as measured by the ASTM D-2386 method, is presently the specification property used to assure low temperature fuel flowability. Consequently, D-2386 equipment is widely available.

An effort was made to identify a less restrictive or better suited fuel property or test method that assures satisfactory aircraft operation in extremely low temperature conditions. Pour point, ASTM D-97, is not a controlled parameter in the specifications for aviation turbine fuels. The method is time consuming and relatively inaccurate. In 1962, a two-jar version of D-97 used to test jet fuel "Solid Point" with a precision of 2°C was included in the D-1655 specification on a tentative basis. It was dropped when the D-2386 Freezing Point Test replaced the D-1477 test. Additional low temperature property tests are described in Appendix C. These methods were considered as far as the available data on the test fuels would permit; however, none were found to accurately predict holdup. More work should be done on some of these methods. The ASTM Technical Division D2-J is examining alternative low temperature fuel test methods.

V. CONCLUSIONS

- The Lockheed and Boeing simulators show similar effects. When simulating the low temperature exposure of an aircraft tank at cruise altitudes, a very steep thermal gradient is observed between the skins of the aircraft and the first few centimeters of fuel next to the skins. Because of the low thermal conductivity of fuel and the minimum amount of convective heat transfer, bulk fuel temperatures lag far behind skin temperatures.

  Wax crystals appear in the fuel boundary layer when boundary layer temperatures fall below the fuel's freezing point. Holdup of wax (and entrained fuel) was measured in both simulators and provided similar results.

- Vibration, slosh, and combined vibration and slosh tended to decrease the difference between simulator skin temperature and bulk fuel temperature.

- The procedure used in the simulator testing for reconstituting the wax phase with the liquid phase after each test did not appear to affect fuel holdup results when the samples were reused as judged by tests using a laboratory test device.

- Holdup in the simulators correlates well with the approximate average of the fuel freezing point and pour point.

- No single bench test of fuel low temperature properties has yet been identified as better suited than freezing point for specifying low temperature operating limits. Freeze point is a conservative measure of these limits.

VI. RECOMMENDATIONS

These recommendations for areas of further work to define fuel low temperature behavior in aircraft are based partly on results from the Boeing and Lockheed test programs and partly on the experience of the members of the CRC group on Low Temperature Flow Properties of Aviation Turbine Fuels. These items are grouped into similar areas and are not in an order of need or preference.

- Obtain additional test data using alternative laboratory low temperature test methods on a complete set of test fuels and correlate results with simulator holdup to determine the best correlation, particularly at low levels of holdup.

- Develop a small-scale laboratory test device where temperature gradients in the fuel sample would be similar to those observed in the wing tank simulators and then establish a relationship or an effect of fuel properties on holdup.

- Develop well documented and broadly accepted aircraft flight model atmospheres and define realistic worst case flight temperature profiles.

- Develop a computational procedure to determine fuel temperature profiles and the attendant fuel hold-up in aircraft tanks as a function of time and fuel properties for a specified model atmosphere and flight profile.

- Investigate the effects of fuel cooling rate on holdup.

- Develop a heat transfer computer program to model fuel temperature profiles in an aircraft tank based on available data from the Boeing and Lockheed programs, establish limitations of the model, and obtain new data if this is found necessary.

- Obtain detailed in-flight fuel tank temperature distribution for correlation with simulator data and with the test airplane's fuel temperature sensing system.

- Study the release of frozen fuel from aircraft structure under conditions of wing flexing and temperature increase. Concurrently, evaluate the fuel system effects of ingestion of solid fuel fragments into the engine feed system; particularly with respect to the boost pumps, screens, filters, and current de-icing heaters.

- Investigate experimentally what level of holdup under cruise conditions would not affect total availability of fuel from a test tank during simulation of a rapid descent to warmer altitudes.

- Develop correlations to normalize the temperatures of fuel tank probes located at various heights above the skin (and having various penetrations) to a common basis.
- Determine experimentally if flow improvers can reduce holdup at low holdup (below 5%) conditions and study the effects of flow-improved wax slurries on fuel system component performance.
- Investigate experimentally the effectiveness of methods for adding heat to fuel to avoid unacceptable levels of holdup under cruise.

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REFERENCES

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3. F. J. Stockemer, "Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model," NASA Report CR-159615, 1979.

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T A B L E S

AND

F I G U R E S

TABLE I
[illegible] LOW TEMPERATURE TEST CONDITIONS

FUEL TYPE	[illegible] (SKIN) TEMP.	TEST TYPE & TARGET TEMP., °C(1)						TOTAL NO. OF TESTS
		STATIC	RECIRC.	SLOSH & RECIRC.	EJEC. & RECIRC.	DRY FUEL	DIVIDER	
[illegible]	-7[illegible] -51	[illegible], [illegible] -[illegible]		-4				4
[illegible]	-[illegible] -4[illegible]	-[illegible] -24			-22			3
[illegible](2)	-[illegible] -[illegible]	-[illegible] -1[illegible]						2
[illegible]	-5[illegible]	-1,+[illegible],+10	+8			+3		[illegible]
[illegible]-1	-[illegible] -[illegible]	-24,-7 -3,+2,+6,+9		-27		0,0	-4	10
[illegible]-3	-[illegible]1	-1	+1					2
L[illegible]-4	-43	-2,0	[illegible]					3
[illegible]P-5	-[illegible]2 -47	-14,[illegible],[illegible],+9	-24 +11	-20	-2[illegible]	+9	-8	10
[illegible]	-[illegible] -42 -32	-16,-1[illegible],-7 +7,+[illegible],+11 +8	-4 +13	-4		+12	-10,-3	13
[illegible]-7	-[illegible]	-4	-2					2
[illegible]P-[illegible]	-63 -57	-1 +3,+[illegible]	+7				+6	5
L[illegible]P-[illegible]	-51	+2,+7,+[illegible]2	+14				+12	[illegible]

(1) TARGET TEMP MEASURED BY THERMOCOUPLE 2.5 CM FROM BOTTOM OF TANK EQUALS FREEZING POINT [illegible] °C

(2) FUEL L-7 IS LFP-5 WITH A FLOW IMPROVER ADDED.

TABLE II

BOEING TEST CONDITIONS AND RUN SEQUENCE

TEST SEQUENCE NO.	FUEL TYPE	CHILLDOWN (SKIN) TEMP °C (°F)	TEST TYPE AND TARGET TEMPERATURE, Δ°C[1]				
			STATIC	SLOSH	VIBRATION	SLOSH & VIBRATION	TOTAL NO. OF RUNS
1	JET A (LFP1)	-50 (-58)	+2.8, 0 -2.8, -5.6	+2.8, 0 -2.8, -5.6	0, -5.6	-5.6	11
2	JET A (LFP8)	-60 (-76)	+2.8, 0 -2.8, 5.6	+2.8, 0 -2.8, -5.6	0, -5.6	-5.6	11
3	JP-8 (SHALE) (B-3)	-57 (-70)	0, -2.8 -5.6	0, -2.8 -5.6	0, -5.6	-5.6	9
4	JP-5+ 9% DFM (B-4)	-46 (-50)	0, -2.8 -5.6	-5.6	-5.6		5
5	JP-8 (PET.) (B-5)	-57 (-70)	0, -2.8 -5.6	0, -2.8 -5.6	0, -5.6	-5.6	9

(1) Target temperature, °C, for control thermocouple 2.54 cm from bottom of tank equals fuel freeze point + Δ°C.

TABLE III

FUELS USED IN TEST PROGRAM

FUEL ID	FUEL TYPE	CRUDE SOURCE	APPROXIMATE FREEZE POINT °C	APPROXIMATE POUR POINT* °C	APPROX. FINAL BOILING POINT °C	SPECIFIC GRAVITY, 15°C
L-1	Jet A	Unknown Petroleum	-38	-52	257	0.8132
L-3	Distillate (Diesel D-2)	Unknown Petroleum	-14	-21	326	0.8612
L-7	Intermediate w/Additive	Paraffinic, Same as LFP-5	-31	-46	294	0.8294
L-8	JP-5	Shale Oil	-34	-37	261	0.8029
LFP-1	Jet A	Paraffinic	-41	-46	267	0.8017
LFP-3	Distillate	Paraffinic	-17	-25	314	0.8285
LFP-4	Distillate	Naphthenic	-14	-30	346	0.8545
LFP-5	Intermediate	Paraffinic	-28	-33	295	0.8299
LFP-6	Intermediate	Naphthenic	-28	-35	282	0.8478
LFP-7	Distillate	Paraffinic Same as LFP-1	-10	-16	316	0.8251
LFP-8	Jet A	Naphthenic, Same as LFP-6	-52	-53	263	0.8273
LFP-9	Jet A	Paraffinic, Same as LFP-3	-46	-48	255	0.8001
B-3	JP-8	Shale	-50	-54	-	-
B-4	JP5 + 9%DFM	Unknown Petroleum	-25	-51	-	-
B-5	JP-8	Unknown Petroleum	-44	-48	-	-

* Average of all available pour point data on these fuels.

TABLE IV

SUMMARY OF BOEING AND LOCKHEED SIMULATOR TEST DATA
(See last page of Table IV for explanation of terms)

OBS	RUN	FUEL	FP	BP	SI	TS	TD	TM	SIMTS	TMMTS	RATIO	HU	HUC	DELTA
1	19	I-3	-14	-21	-37.894	-60	-54.5	-19.5	42.1059	40.5	1.03965	68.4	40.0261	-28.376
2	31	LFP-1	-41	-46	-44.206	-70	-66.5	-43.0	25.7938	27.0	0.95533	56.0	27.6441	-28.356
3	36	LFP-1	-41	-46	-44.206	-74	-69.5	-44.0	29.7938	30.0	0.99313	57.2	32.6067	-24.593
4	6	I-1	-38	-52	-45.925	-74	-69.5	-45.0	28.0748	29.0	0.96810	36.3	29.2258	-7.074
5	94	I-7	-31	-46	-39.358	-51	-46.0	-30.3	11.6418	20.7	0.56241	10.2	5.1470	-5.053
6	204	LFP-8	-52	-53	-53.241	-62	-58.3	-48.0	8.7587	14.0	0.62562	11.2	6.7568	-4.443
7	117	LFP-1	-41	-46	-44.206	-50	-46.8	-39.0	5.7938	12.0	0.48282	8.0	3.6243	-4.375
8	213	LFP-8	-52	-53	-53.241	-61	-55.2	-44.0	7.7587	17.0	0.45639	6.6	3.2158	-3.384
9	208	LFP-8	-52	-53	-53.241	-61	-57.6	-48.0	7.7587	13.0	0.59682	9.2	5.9719	-3.228
10	26	LFP-5	-28	-33	-31.028	-59	-50.5	-28.7	27.9719	30.3	0.92317	27.1	24.0438	-3.056
11	504	B-5	-44	-48	-46.718	-57	-49.5	-38.0	10.2816	19.0	0.54114	7.5	4.6917	-2.808
12	508	B-5	-44	-48	-46.718	-57	-49.8	-38.0	10.2816	19.0	0.54114	7.4	4.6917	-2.708
13	60	LFP-1	-41	-46	-44.206	-51	-46.5	-37.4	6.7938	13.6	0.49954	6.5	3.9056	-2.594
14	79	I-8	-34	-37	-36.052	-52	-39.0	-13.8	15.9475	38.2	0.41747	5.2	2.6856	-2.514
15	53	I-1	-38	-52	-45.925	-51	-47.5	-36.6	5.0748	14.4	0.35242	4.3	1.9584	-2.342
16	100	I-7	-31	-46	-39.358	-63	-56.0	-33.8	23.6418	29.2	0.80965	17.1	14.7752	-2.325
17	1811	LFP-1	-41	-46	-44.206	-54	-47.0	-38.0	9.7938	16.0	0.61211	8.7	6.3771	-2.323
18	5411	B-5	-44	-48	-46.718	-58	-51.2	-42.0	11.2816	16.0	0.70510	11.4	9.4768	-1.923
19	73	LFP-9	-45	-48	-47.688	-52	-47.0	-35.4	4.3120	15.6	0.27641	3.2	1.3352	-1.896
20	102	LFP-1	-41	-46	-44.206	-49	-44.0	-30.0	4.7938	19.0	0.25231	2.8	1.1347	-1.665
21	92	LFP-8	-52	-53	-53.241	-63	-56.0	-43.1	9.7587	19.9	0.49039	5.2	3.7493	-1.451
22	42	LFP-6	-28	-35	-32.086	-49	-38.5	-19.0	16.9141	30.0	0.56380	6.6	5.1783	-1.422
23	82	I-3	-34	-37	-36.052	-50	-39.0	-2.7	13.9475	47.3	0.29487	2.7	1.4481	-1.252
24	78	I-8	-34	-37	-36.052	-50	-34.5	-0.5	13.9475	49.5	0.28177	2.5	1.3464	-1.154
25	71	LFP-5	-28	-33	-31.028	-50	-33.0	-11.0	18.9719	39.0	0.48646	4.8	3.6840	-1.116
26	3810	B-3	-50	-54	-52.801	-58	-56.3	-49.0	5.1994	9.0	0.57771	6.6	5.4987	-1.100
27	119	LFP-1	-41	-46	-44.206	-50	-43.8	-35.0	5.7938	15.0	0.38625	3.3	2.3141	-0.986
28	109	4-3	-50	-54	-52.801	-57	-52.5	-42.0	4.1994	15.0	0.27996	2.3	1.3327	-0.967
29	5410	B-5	-44	-48	-46.718	-57	-49.7	-42.0	10.2816	15.0	0.68544	9.6	8.7178	-0.882
30	41	LFP-6	-28	-35	-32.086	-50	-41.0	-23.0	17.9141	27.0	0.66349	8.8	7.9409	-0.859
31	54	I-1	-38	-52	-45.925	-51	-44.0	-35.7	5.0748	15.3	0.33169	2.6	1.7518	-0.838
32	63	LFP-6	-28	-35	-32.086	-38	-27.0	-3.9	5.9141	34.1	0.17343	1.5	0.6677	-0.832
33	72	LFP-9	-46	-48	-47.688	-51	-43.5	-25.9	3.3120	25.1	0.13195	1.2	0.4699	-0.730
34	57	LFP-1	-41	-46	-44.206	-50	-42.0	-20.9	5.7938	29.1	0.19910	1.5	0.8054	-0.695
35	507	B-5	-44	-48	-46.718	-56	-46.0	-33.0	9.2816	23.0	0.40355	3.2	2.5144	-0.686
36	509	B-5	-44	-48	-46.718	-56	-46.2	-32.0	9.2816	24.0	0.38673	3.0	2.3195	-0.680
37	49	LFP-6	-28	-35	-32.086	-51	-46.0	-29.7	18.9141	21.3	0.88799	21.3	20.6587	-0.641
38	512	B-5	-44	-48	-46.718	-56	-45.7	-36.0	9.2816	20.0	0.46408	3.9	3.3303	-0.570
39	81	I-8	-34	-37	-36.052	-50	-33.0	-12.3	13.9475	37.7	0.36996	2.7	2.1371	-0.563
40	67	LFP-5	-28	-33	-31.028	-47	-31.5	-7.6	15.9719	39.4	0.40538	3.0	2.5364	-0.466
41	76	LFP-9	-46	-48	-47.688	-51	-39.5	-17.6	3.3120	33.4	0.09916	0.7	0.3326	-0.367
42	65	LFP-6	-28	-35	-32.086	-32	-24.0	-7.3	-0.0859	24.7	-0.00348	0.3	-0.0098	-0.310
43	75	LFP-9	-46	-48	-47.688	-51	-39.5	-22.3	3.3120	28.7	0.11540	0.7	0.3996	-0.301
44	80	I-8	-34	-37	-36.052	-47	-31.0	3.1	10.9475	50.1	0.21851	1.2	0.9183	-0.282
45	422	B-4	-25	-51	-39.094	-45	-27.7	-18.0	5.9061	27.0	0.21874	1.2	0.9197	-0.280
46	434	B-4	-25	-51	-39.094	-47	-33.5	-21.0	7.9061	26.0	0.30408	1.8	1.5226	-0.277
47	88	LFP-8	-52	-53	-53.241	-55	-49.5	-37.8	1.7587	17.2	0.10225	0.6	0.3468	-0.255
48	70	LFP-5	-28	-33	-31.028	-44	-26.5	-0.1	12.9719	43.9	0.29549	1.7	1.4530	-0.247
49	43	LFP-6	-28	-35	-32.086	-49	-36.0	-18.5	16.9141	30.5	0.55456	5.2	4.9745	-0.225
50	55	LFP-1	-41	-46	-44.206	-50	-43.5	-26.2	5.7938	23.8	0.24344	1.3	1.0754	-0.225
51	90	LFP-8	-52	-53	-53.241	-55	-49.5	-39.4	1.7587	15.6	0.11274	0.6	0.3875	-0.212
52	74	LFP-9	-46	-48	-47.688	-50	-39.5	-17.1	2.3120	32.9	0.07027	0.4	0.2239	-0.176

TABLE IV

SUMMARY OF BOEING AND LOCKHEED SIMULATOR TEST DATA
(See last page of Table IV for explanation of terms)

OBS	RUN	FUEL	FP	PP	SI	TS	TO	TM	SIMTS	TMMTS	RATIO	HU	HUC	DELTA
53	207	LFP-3	-52	-53	-53.241	-61	-55.0	-45.0	7.7587	16.0	0.48492	3.8	3.6586	-0.14140
54	66	LFP-6	-28	-35	-32.086	-41	-25.0	1.5	8.9141	42.5	0.20974	1.0	0.8664	-0.13364
55	303	B-3	-50	-54	-52.801	-57	-54.0	-43.0	4.1994	14.0	0.29996	1.6	1.4889	-0.11105
56	3011	B-3	-50	-54	-52.801	-59	-56.3	-49.0	6.1994	10.0	0.61994	6.7	6.5945	-0.10549
57	61	LFP-6	-28	-35	-32.086	-51	-34.5	-15.8	18.9141	35.2	0.53733	4.6	4.6143	0.01426
58	302	B-3	-50	-54	-52.801	-59	-56.3	-49.0	6.1994	10.0	0.61994	6.5	6.5945	0.09451
59	68	LFP-5	-28	-33	-31.028	-45	-26.5	0.8	13.9719	45.8	0.30506	1.4	1.5307	0.13072
60	423	B-4	-25	-51	-39.094	-47	-30.8	-20.0	7.9061	27.0	0.29282	1.3	1.4319	0.13185
61	61	LFP-6	-28	-35	-32.086	-44	-29.0	0.4	11.9141	44.4	0.26834	1.1	1.2471	0.14706
62	69	LFP-5	-28	-33	-31.028	-45	-26.5	-4.3	13.9719	40.7	0.34329	1.7	1.8700	0.14997
63	91	LFP-8	-52	-53	-53.241	-59	-51.5	-40.6	4.7587	17.4	0.27349	1.1	1.2846	0.18459
64	315	H-3	-50	-54	-52.801	-57	-50.2	-41.0	4.1994	16.0	0.26246	1.0	1.2051	0.20514
65	58	LFP-1	-41	-46	-44.206	-50	-40.5	-17.0	5.7938	33.0	0.17557	0.4	0.6787	0.27867
66	45	LFP-7	-10	-16	-13.310	-44	-20.5	4.2	30.6896	48.2	0.63671	6.8	7.0867	0.28468
67	84	LFP-6	-28	-35	-32.086	-50	-40.0	-25.8	17.9141	24.2	0.74025	10.7	11.0013	0.30127
68	503	H-5	-44	-48	-46.718	-56	-47.7	-35.0	9.2816	21.0	0.44198	2.7	3.0101	0.31005
69	10	L-1	-38	-52	-45.925	-69	-65.0	-46.0	23.0748	23.0	1.00325	33.7	34.0886	0.38855
70	62	LFP-6	-28	-35	-32.086	-43	-25.0	0.2	10.9141	43.2	0.25264	0.7	1.1370	0.43702
71	307	B-3	-50	-54	-52.801	-57	-54.2	-43.0	4.1994	14.0	0.29996	1.0	1.4889	0.48895
72	114	LFP-1	-41	-46	-44.206	-52	-48.0	-42.0	7.7938	10.0	0.77938	12.5	12.9897	0.48970
73	96	LFP-8	-52	-53	-53.241	-59	-49.5	-35.9	4.7587	22.1	0.21533	0.4	0.8993	0.49926
74	302	B-3	-50	-54	-52.801	-57	-51.2	-39.0	4.1994	18.0	0.23330	0.5	1.0098	0.50979
75	506	H-5	-44	-48	-46.718	-57	-45.7	-33.0	10.2816	24.0	0.42840	2.3	2.8265	0.52646
76	54	LFP-1	-41	-46	-44.206	-48	-37.5	-28.0	3.7938	20.0	0.18969	0.2	0.7535	0.55346
77	64	LFP-6	-28	-35	-32.086	-43	-25.0	-1.1	10.9141	41.9	0.26048	0.6	1.1912	0.59110
78	418	B-4	-25	-51	-39.094	-45	-32.8	-19.0	6.9061	27.0	0.25578	0.5	1.1585	0.65854
79	106	LFP-1	-41	-46	-44.206	-55	-45.0	-33.0	10.7938	22.0	0.49063	3.0	3.7533	0.75333
80	47	LFP-4	-14	-30	-22.654	-43	-22.0	4.0	20.3458	47.0	0.43289	2.1	2.8861	0.78609
81	209	LFP-8	-52	-53	-53.241	-59	-52.5	-42.0	5.7587	17.0	0.33875	1.0	1.8271	0.82707
82	50	LFP-3	-17	-25	-21.464	-42	-22.5	3.1	20.5359	45.1	0.45534	2.3	3.2003	0.90034
83	51	LFP-3	-17	-25	-21.464	-42	-20.0	2.1	20.5359	44.1	0.46567	2.4	3.3543	0.95433
84	4810	B-4	-25	-51	-39.094	-46	-31.5	-19.0	6.9061	27.0	0.25578	0.2	1.1585	0.95854
85	49	LFP-4	-14	-30	-22.654	-42	-19.5	3.7	19.3458	45.7	0.42332	1.7	2.7602	1.06025
86	201	LFP-8	-52	-53	-53.241	-59	-50.0	-38.0	5.7587	21.0	0.27422	0.2	1.2900	1.09000
87	206	LFP-8	-52	-53	-53.241	-59	-51.8	-40.0	5.7587	19.0	0.30309	0.4	1.5145	1.11448
88	105	LFP-1	-41	-46	-44.206	-52	-43.0	-30.0	7.7938	22.0	0.35426	0.8	1.9767	1.17666
89	44	LFP-6	-28	-35	-32.086	-49	-38.0	-21.2	16.9141	27.8	0.60842	5.1	6.2769	1.17492
90	86	LFP-5	-28	-33	-31.028	-51	-38.0	-21.0	19.9719	30.0	0.66573	6.8	8.0171	1.21710
91	103	LFP-1	-41	-46	-44.206	-54	-47.0	-35.0	9.7938	19.0	0.51546	2.9	4.1912	1.29125
92	46	LFP-4	-14	-30	-22.654	-43	-19.5	8.6	20.3458	51.6	0.39430	1.1	2.4057	1.30566
93	202	LFP-8	-52	-53	-53.241	-60	-52.8	-40.0	6.7587	20.0	0.33794	0.5	1.8195	1.31968
94	205	LFP-8	-52	-53	-53.241	-61	-51.0	-40.0	7.7587	21.0	0.36946	0.8	2.1319	1.33191
95	56	LFP-1	-41	-46	-44.206	-51	-43.5	-37.3	6.7938	13.7	0.49590	2.5	3.8427	1.34271
96	85	LFP-1	-41	-46	-44.206	-52	-46.5	-38.6	7.7938	13.4	0.58163	4.2	5.5935	1.39349
97	101	LFP-1	-41	-46	-44.206	-50	-43.0	-34.0	5.7938	16.0	0.36211	0.6	2.0557	1.45572
98	34	LFP-1	-41	-46	-44.206	-67	-53.0	-40.7	22.7938	26.3	0.86668	17.1	18.8527	1.75268
99	24	LFP-5	-28	-33	-31.028	-65	-57.5	-27.0	33.9719	38.0	0.89400	19.3	21.2001	1.90006
100	304	B-3	-50	-54	-52.801	-59	-56.3	-50.0	6.1994	9.0	0.68882	6.8	8.8439	2.04395
101	46	LFP-7	-10	-16	-13.310	-42	-18.0	3.5	28.6896	45.6	0.62916	4.5	6.8597	2.35968
102	198	LFP-1	-41	-46	-44.206	-52	-48.8	-43.0	7.7938	9.0	0.86598	16.1	18.7956	2.69566
103	52	LFP-3	-17	-25	-21.464	-41	-18.5	-4.5	19.5359	36.5	0.53523	1.7	4.5720	2.87197
104	2810	LFP-8	-52	-53	-53.241	-61	-57.5	-51.0	7.7587	10.0	0.77587	9.2	12.7974	3.59737

TABLE IV

SUMMARY OF BOEING AND LOCKHEED SIMULATOR TEST DATA

OBS	RUN	FUEL	FP	PP	SI	TS	TD	TM	SIMTS	TMMTS	RATIO	HU	HUC	DELTA
105	2011	LFP-5	-52	-53	-53.241	-61	-58.2	-51.0	7.7587	10.0	0.77587	9.2	12.7974	3.5974
106	22	L-3	-14	-21	-17.894	-46	-39.5	-13.0	28.1059	33.0	0.85169	13.5	17.6801	4.1801
107	26	LFP-5	-28	-33	-31.028	-60	-44.0	-29.0	28.9719	31.0	0.93458	20.8	25.2619	4.4619
108	21	LFP-5	-28	-33	-31.028	-47	-43.5	-29.2	15.9719	17.8	0.89730	16.7	21.5035	4.8035
109	12	L-3	-14	-21	-17.894	-44	-39.5	-20.0	26.1059	24.0	1.08775	42.0	49.5869	7.5869
110	1010	LFP-1	-41	-46	-44.206	-55	-49.0	-44.0	10.7938	11.0	0.98125	8.5	30.9548	22.4548

DEFINITION OF TERMS

OBS = TEST RUN NUMBER ASSIGNED BY BOEING AND/OR LOCKHEED. RUNS = <100 MADE BY LOCKHEED, OTHERS BY BOEING.

FUEL = FUEL NUMBERS USED BY BOEING AND/OR LOCKHEED.

FP = FUEL FREEZE POINT, °C, BY ASTM D 2386.

PP = FUEL POUR POINT, °C, BY ASTM D 97.

SI = SOLIDIFICATION INDEX = 0.5289 PP + 0.484 FP.

TS = TANK SKIN TEMPERATURE, °C.

TD = FUEL TEMPERATURE 1.3 cm FROM BOTTOM OF TANK, °C.

TM = FUEL TEMPERATURE IN MIDDLE OF TANK, °C.

SIMTS = SI MINUS TS, °C.

TMMTS = TM MINUS TS, °C.

RATIO = SIMTS/TMMTS.

HU = OBSERVED HOLDUP, %.

HUC = ESTIMATED HOLDUP, %.

DELTA = HUC MINUS HU.

TABLE V

SUMMARY OF SPECIAL LOW TEMPERATURE TESTS

	LFP-1	LFP-3	LFP-4	LFP-5	LFP-6	LFP-7	LFP-9
Freeze Point, °C (D 2386)	-40	-15	-11	-26	-27	- 9	-43
	-40	-15	-12	-27	-26.5	-11	-49
	-41	-17	-17	-28	-31	-11	-46
	-42	-19	-16	-30	-29	- 7	-46
	-41	-17		-28			-46
Pour Point, °C	-46	-26	-26	-34	-37	-18	-51
				-31	-31		
	-43	-21	-21	-32	-34	-15	-46
	-50	-33	-42	-35	-38	-17	-48
		-20				-15	
Cloud Point, °C	-41	-21	-14	-31	-32	-12	-47
	-44	-20	-16	-30	-31	-12	-47
		-15				-11	
Cold Flow Zero Holdup, °C	-43	-15	-24	-30	-30	-15	-45
Shell Cloud/Pour Analyzer							
TXP, °C	-37	-15	-	-24	-27	-11	-36
TSP, °C	-47	-30	-37	-32	-36	-18	-48
Setapoint Detector, °C	-42	-19	-18	-30	-30	-15	-45.5
Enjay Fluidity Test, °C	-40	-18	-20	-29	-29	-16	-43
Cold Filter Plugging Point Test, °C	-47	-22	-16	-32	-34	-16	-52
Calculated Solidification Index, °C	-44.2	-21.5	-22.7	-31.0	-32.1	-13.3	-47.7

* From Reference No. 2.

TABLE VI

HOLDUP MEASUREMENTS OF RECYCLED FUEL[1]

(Shell Cold Flow Tester)

FUEL LFP-1[2]	Test A	Test B	Test C
Temp. of Holdup Measurement °C	-44.2	-44.4	-44.6
% Holdup			
New Fuel	12.0	10.5	9.5
Recycle #1	11.5	6.0	6.0
Recycle #2	10.5	5.5	4.0
Recycle #3		6.5	4.0
Recycle #4		11.0	8.5

FUEL LFP-8[3]	Test A	Test B	Test C	Test D	Test E	Test F
Temp. of Holdup Meas. °C	-53.2	-53.3	-53.2	-53.2	-53.2	-53.3
% Holdup						
New Fuel	11.0	10.0	6.5	8.0	7.0	12.0
Recycle #1	11.0	11.0	11.0	15.0	14.0	11.0
Recycle #2	10.5	11.0	10.0	10.0	16.0	12.0
Recycle #3	12.0	8.5		14.0		14.0

---

(1) Tests on a new sample followed by several cycles of remixing the separated components and retesting.

(2) Boeing data from Figure 10 shows a holdup variation from 5 to 60% at about -44°C.

(3) Boeing data from Figure 4 shows a holdup variation from 14 to 60% at about -53°C.

FIGURE 1

INTERIOR VIEW OF BOEING SIMULATOR TANK

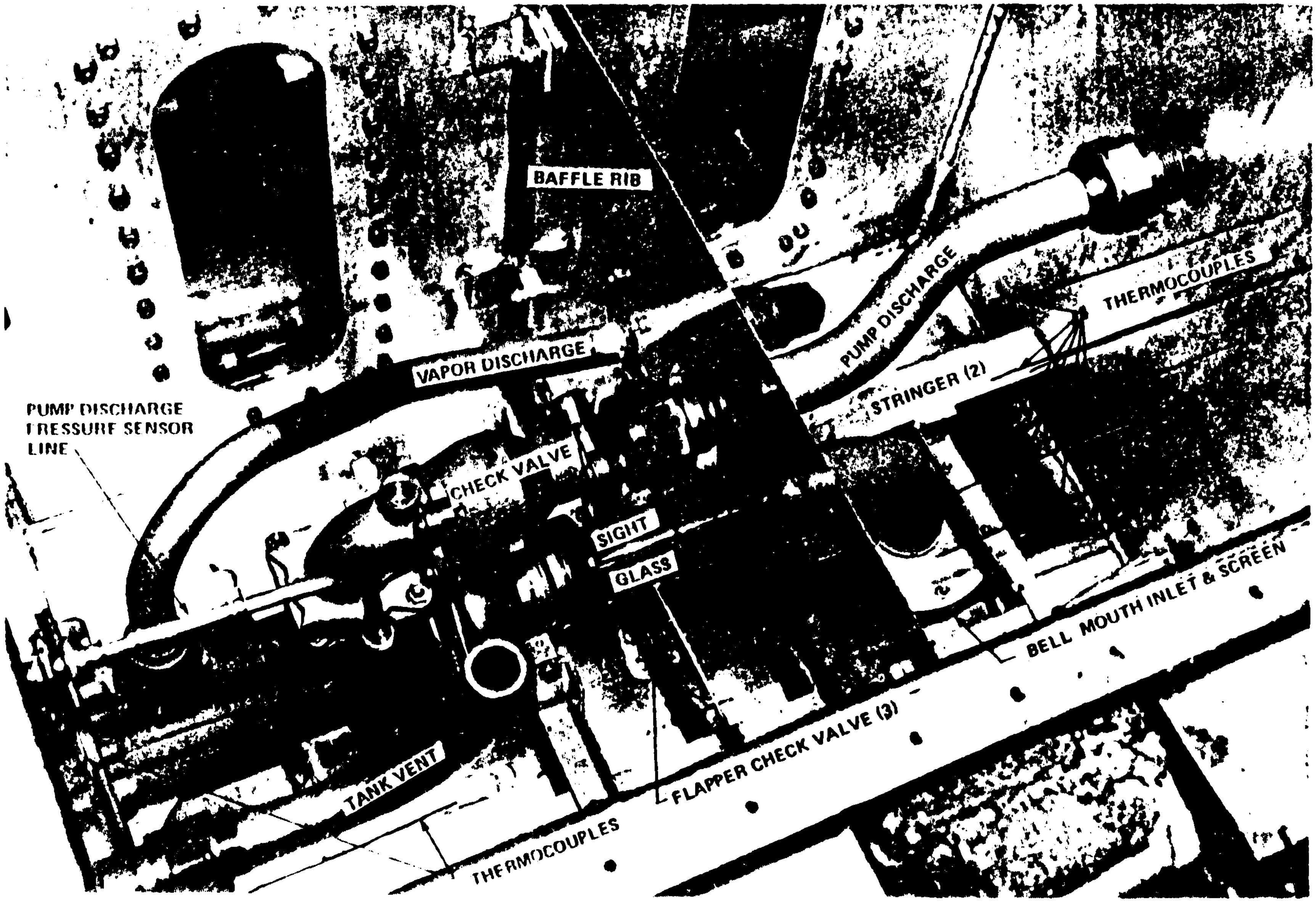


FIGURE 2

INTERIOR VIEW OF LOCKHEED SIMULATOR TANK

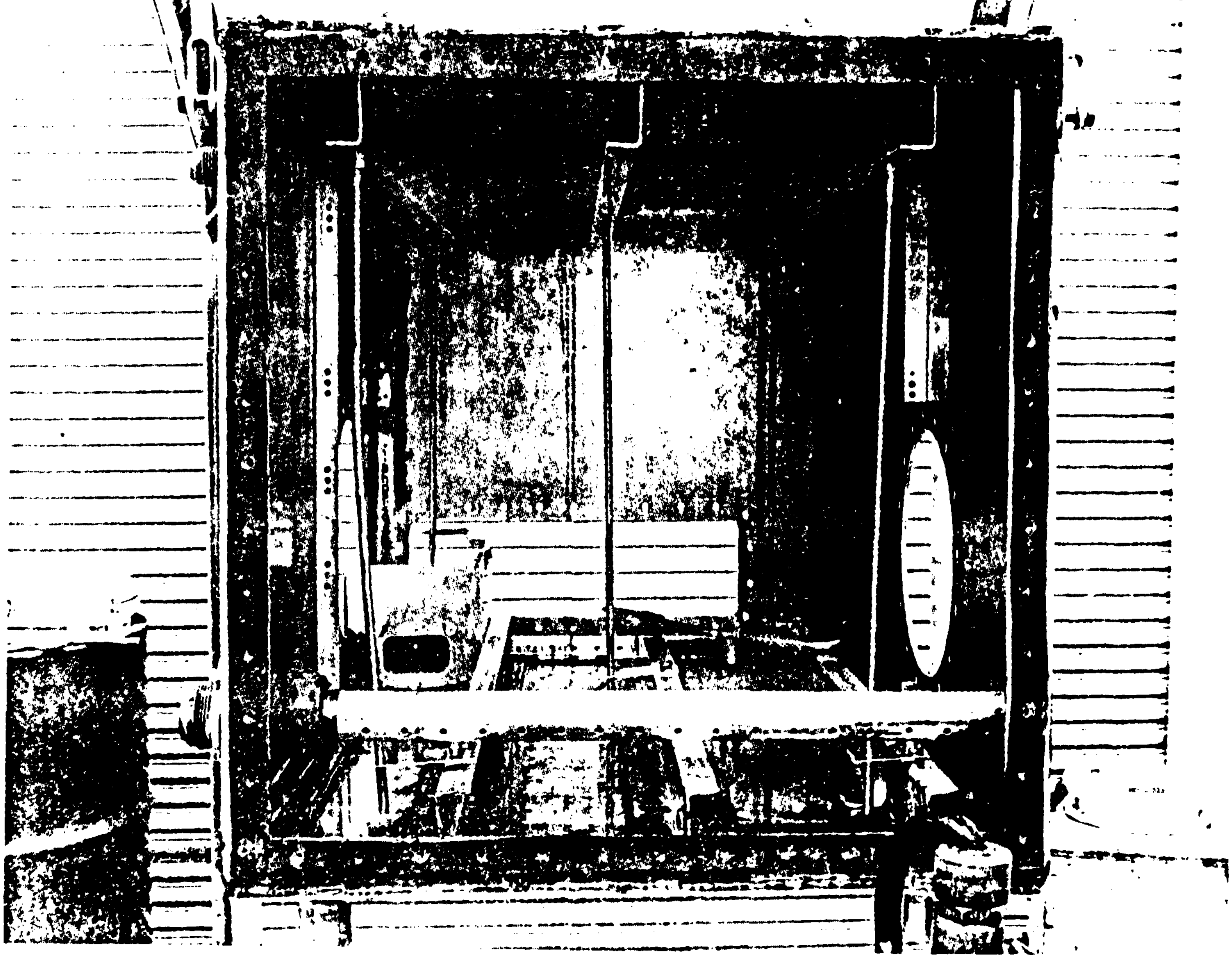


FIGURE 3

VERTICAL TEMPERATURE PROFILES AT START OF FUEL WITHDRAWAL
FUEL (LFP-1)

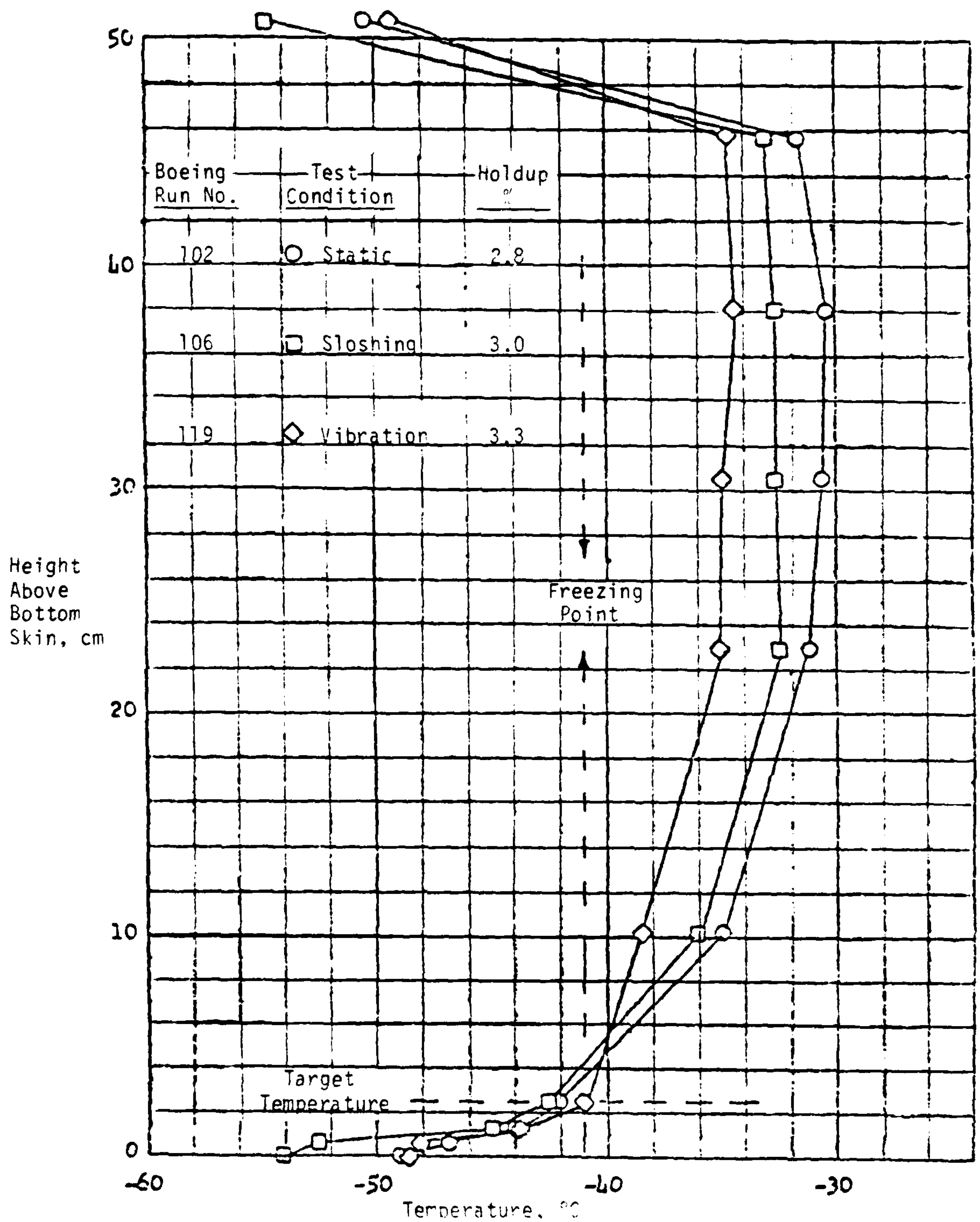


FIGURE 4

TANK FUEL TEMPERATURE PROFILE SCHEMATIC

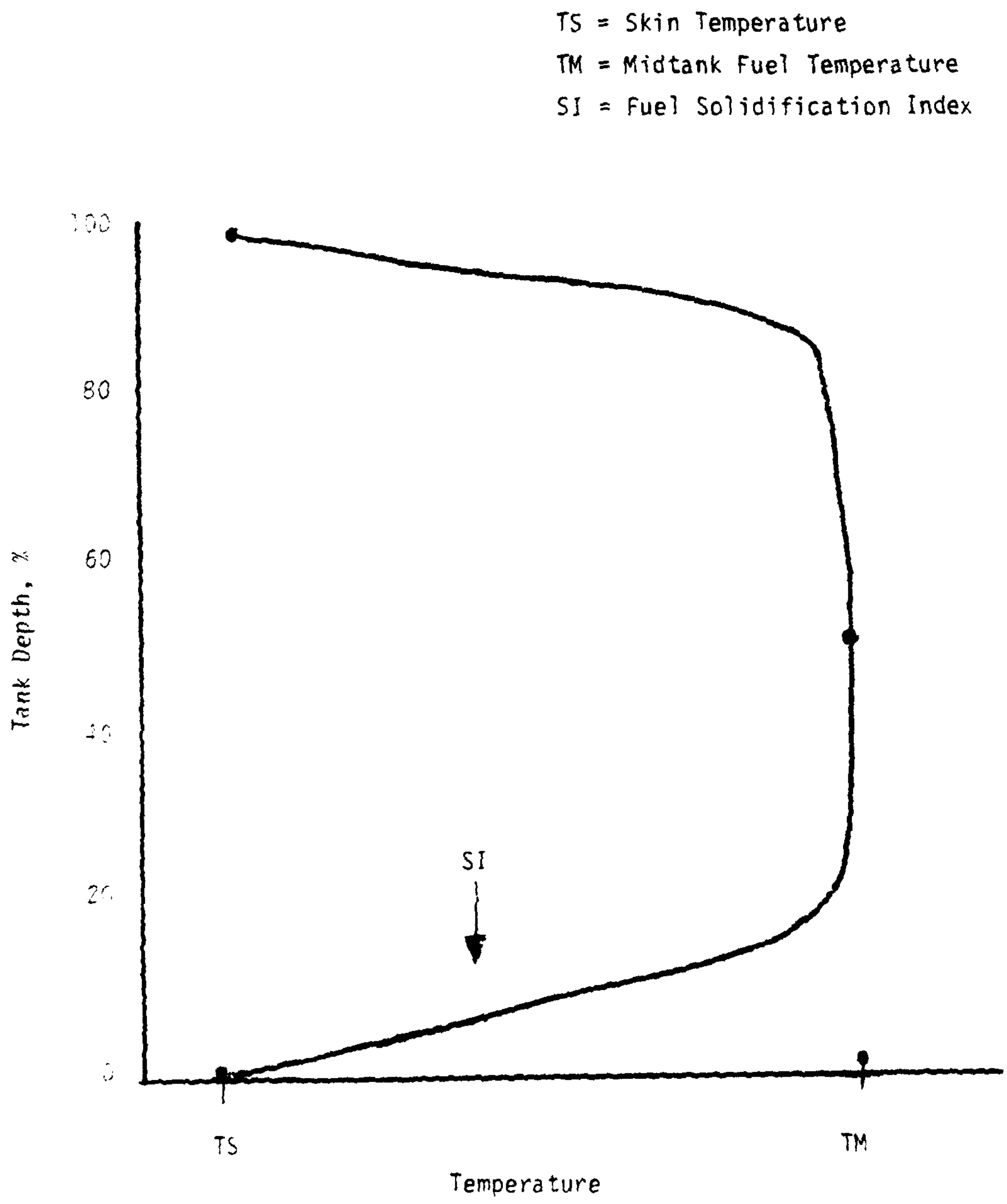
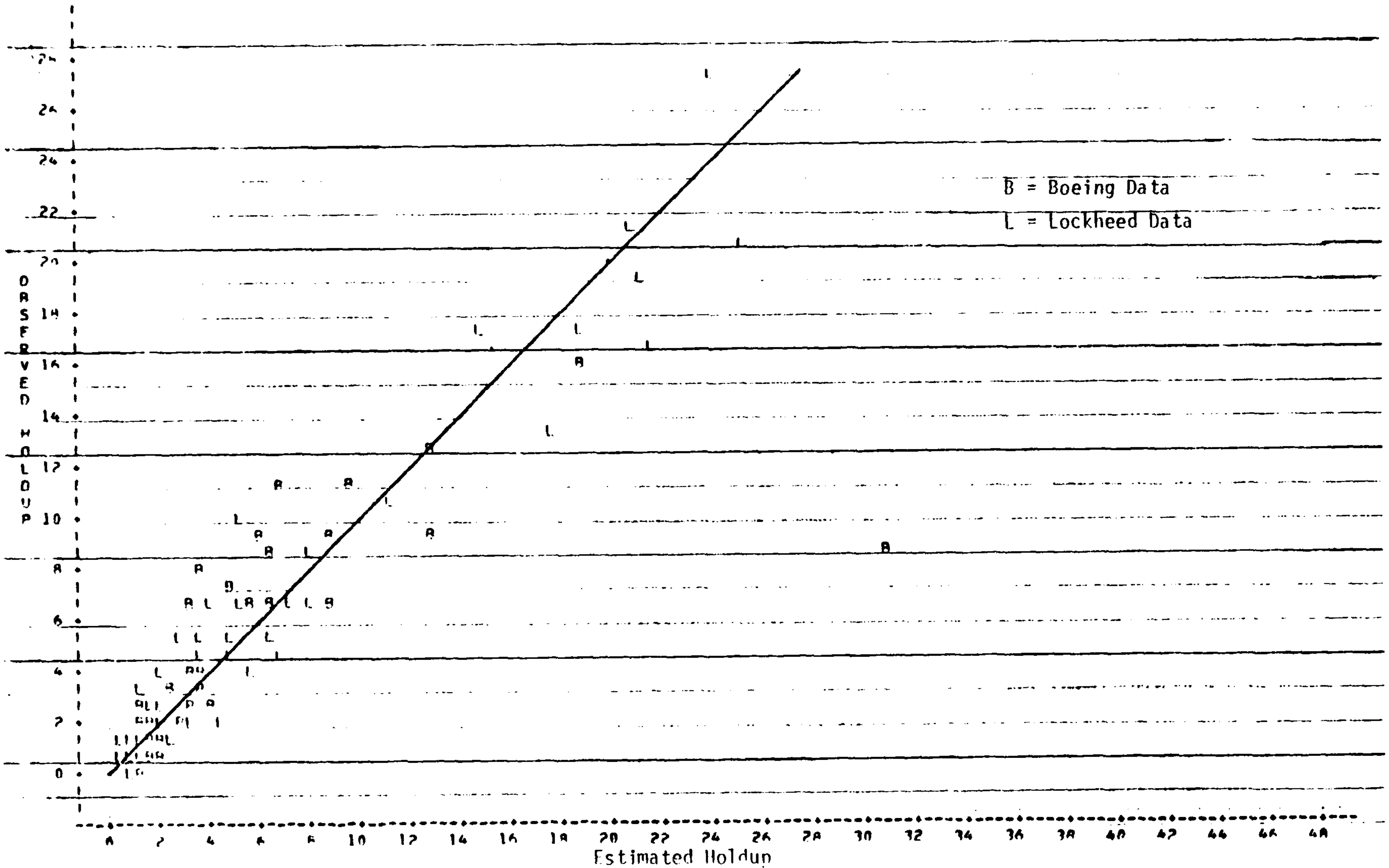


FIGURE 5

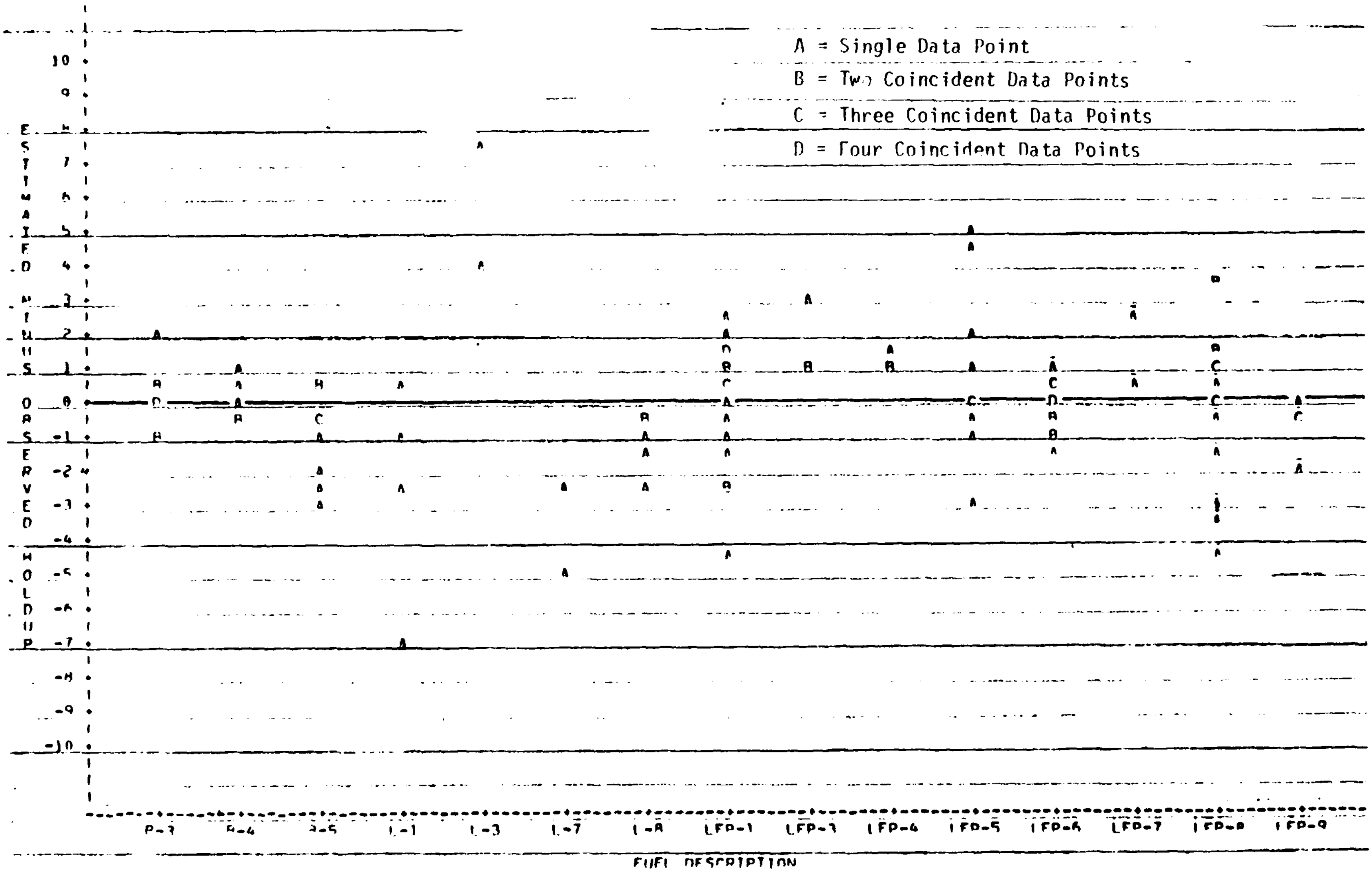
COMPARISON OF OBSERVED AND ESTIMATED HOLDUP



Note: 7 OBS had missing values or were out of range.
35 OBS hidden by coincident data points.

FIGURE 6

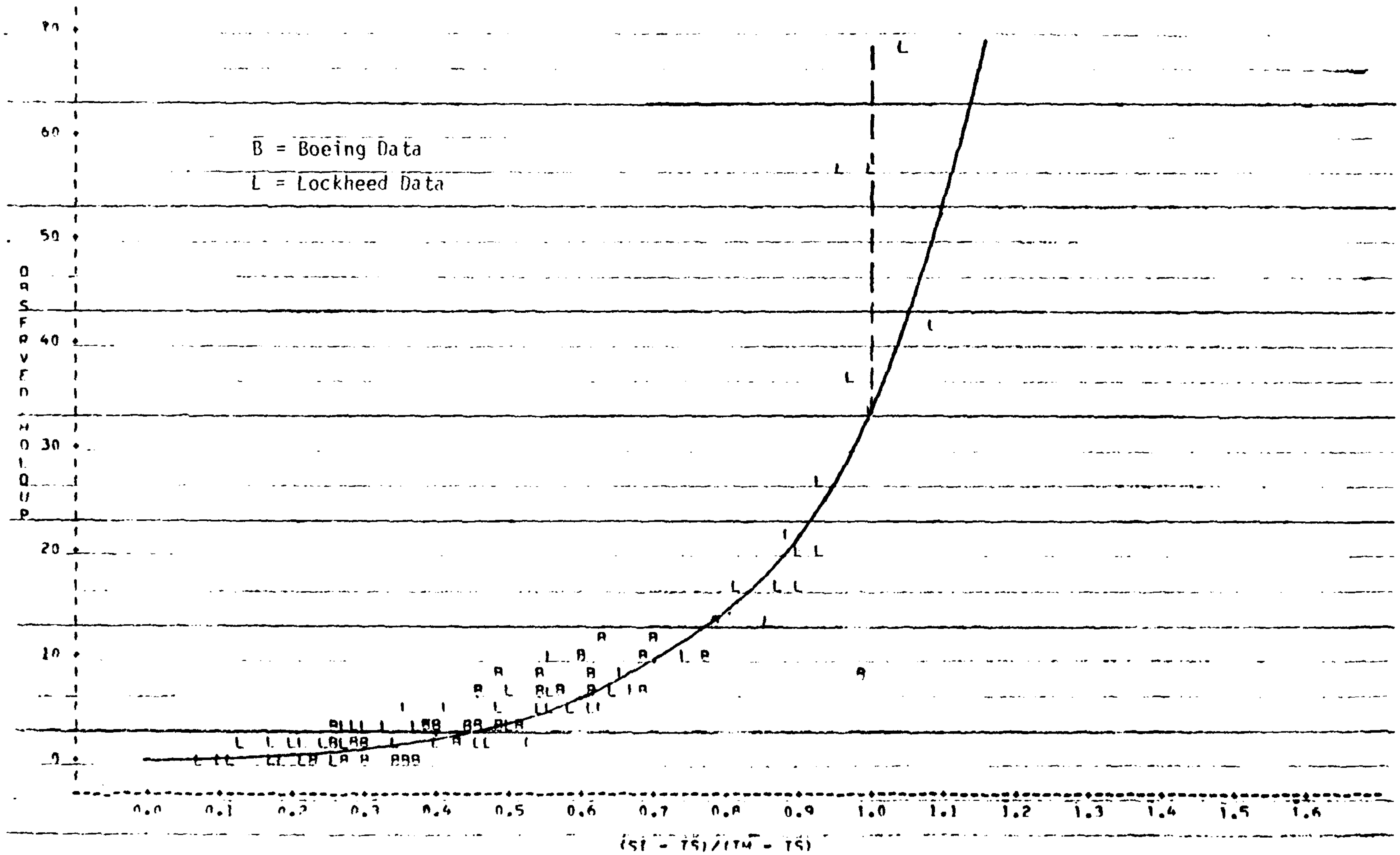
DIFFERENCE BETWEEN ESTIMATED AND OBSERVED HOLDUP BY FUEL TYPE



Note: 4 OBS had missing values or were out of range.

FIGURE 7

HOLDUP AS A FUNCTION OF (SI-TS)/(TM-TS)



Note: 1 OBS had missing values or were out of range.
24 OBS hidden by coincident data points.

TERMS: SI = Fuel Solidification Index
TS = Tank Skin Temperature
TM = Fuel Midtank Temperature

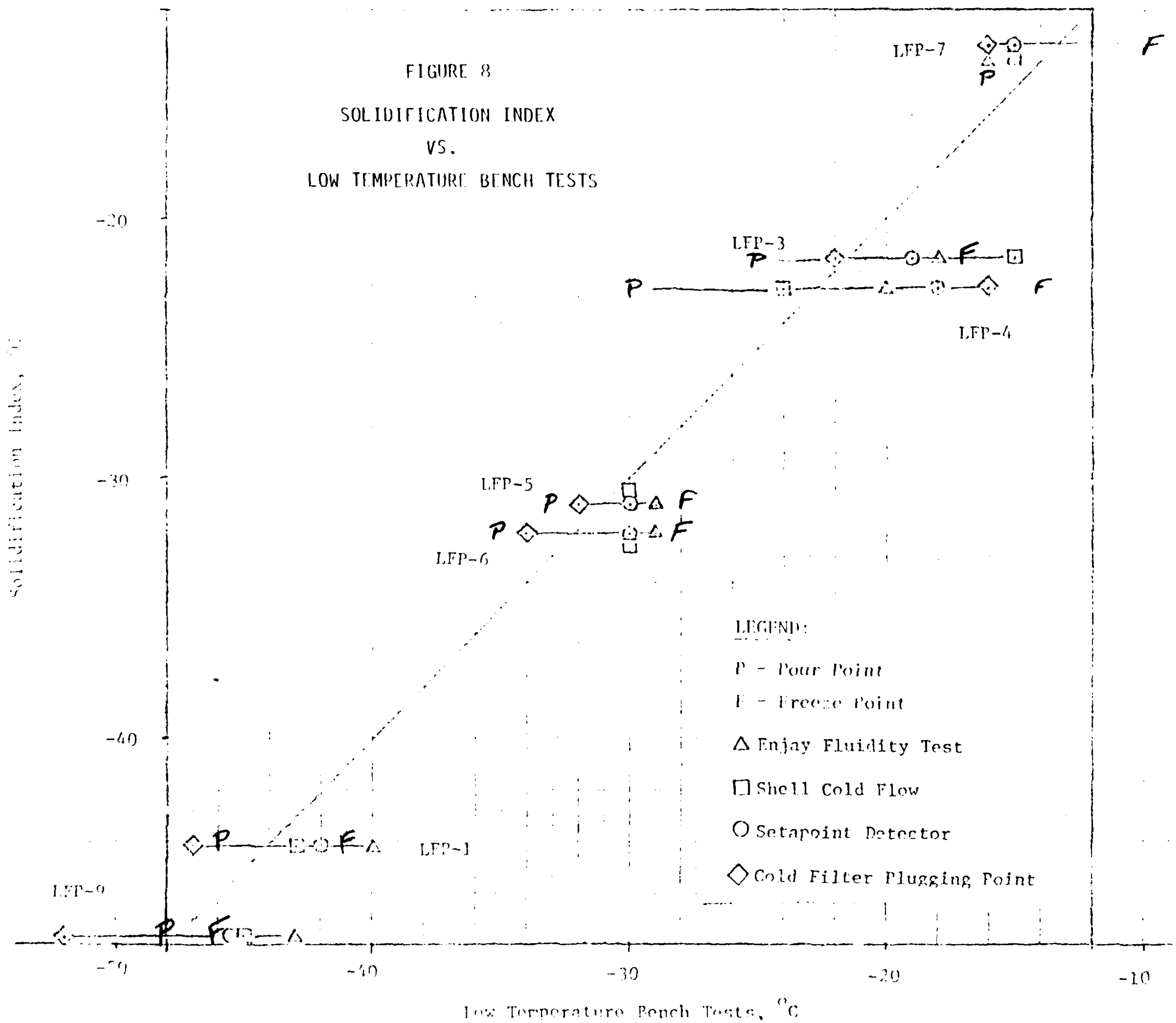


FIGURE 8

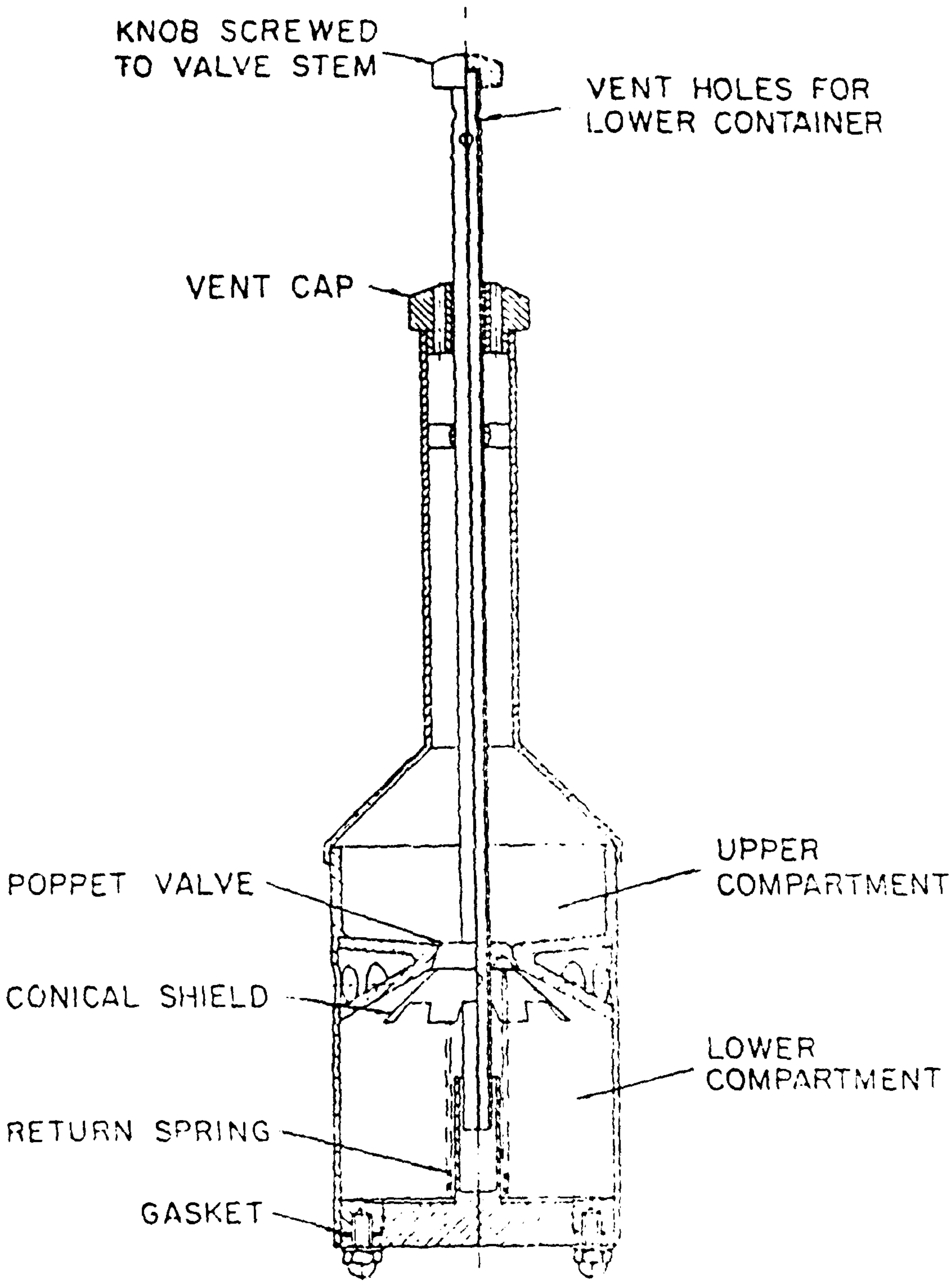
SOLIDIFICATION INDEX

VS.

LOW TEMPERATURE BENCH TESTS

FIGURE 9

SHELL COLD FLOW TESTER - SECTIONAL ELEVATION



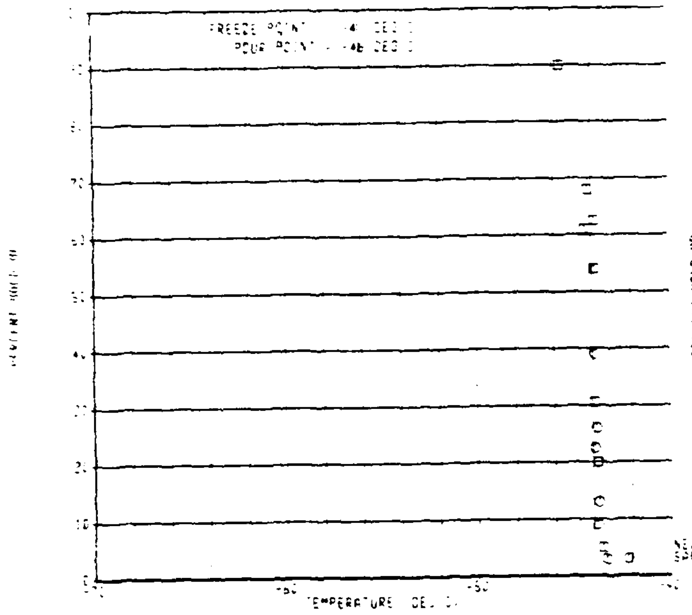


FIGURE 10. SHELL TESTER HOLDUP DATA, FUEL [illegible]

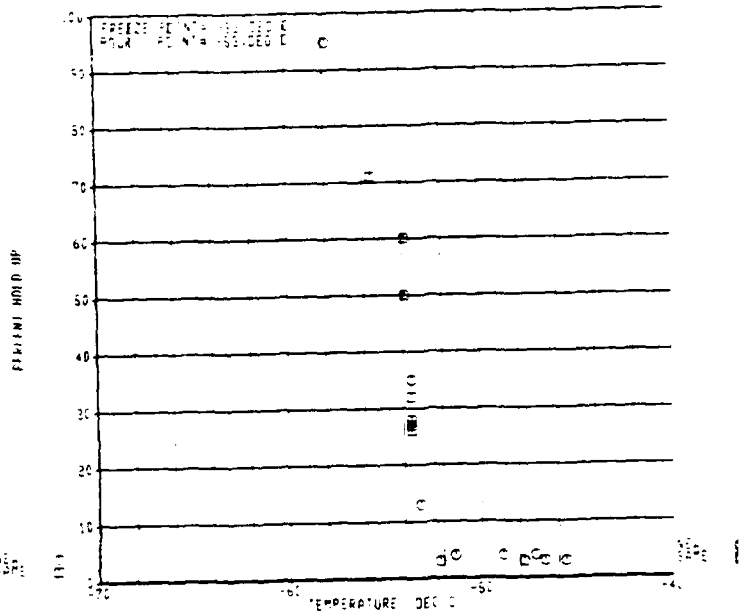


FIGURE [illegible] SHELL TESTER HOLDUP DATA, FUEL [illegible]

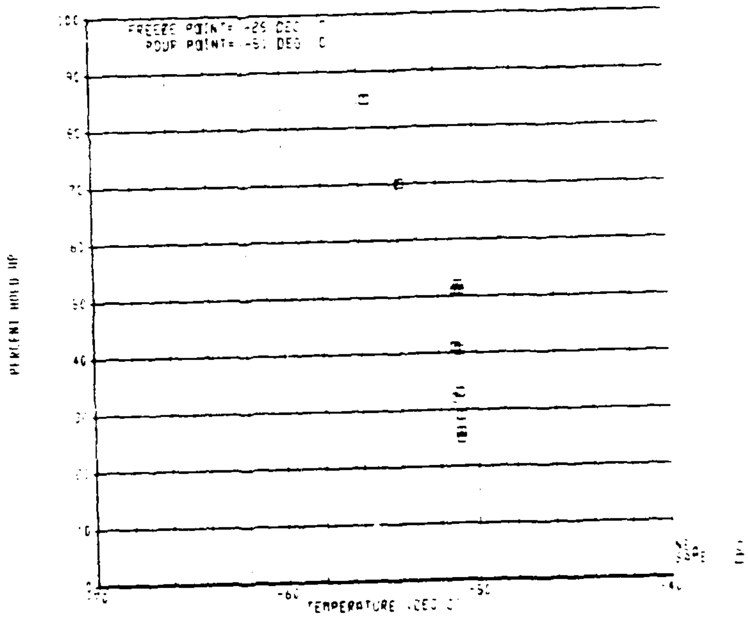


FIGURE 12. SHELL TESTER HOLDUP DATA, FUEL [illegible]

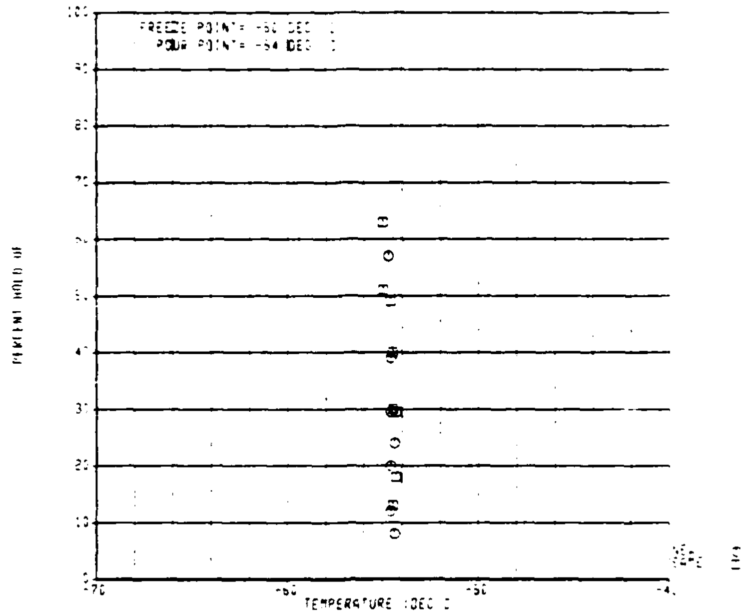


FIGURE 13. SHELL TESTER HOLDUP DATA, JP8 SHALE (FUEL E-3)

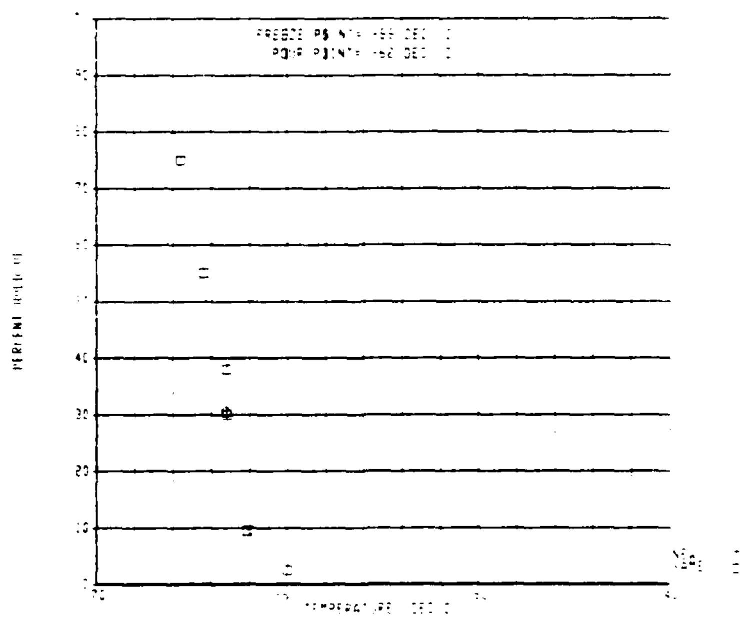


FIGURE 14. SHELL TESTER HOLDUP DATA, JP8 PETROLEUM (OFF SPECIFICATION, NOT USED IN SIMULATOR TESTS)

APPENDIX A

AIRCRAFT DESIGN CONSIDERATIONS

AIRCRAFT DESIGN CONSIDERATIONS

During the development of this report, it became necessary to inquire into certain aircraft design considerations which have bearing on the low temperature fuel problem. The findings are included for reference.

Fuel Management

The recognition that fuel temperature is a function of the location of the fuel in the aircraft tankage has prompted the suggestion that fuel simply be used in a different manner. For example, the fuel in the outboard wing tanks cools more rapidly, is held until late in the flight and reaches a lower temperature than does fuel at the wing root or in a center wing or fuselage tank. From this standpoint, logic says that the outboard fuel should be used first and the inboard fuel which stays warmer should be saved for the later part of the flight. This reversal of procedure is impractical to the airplane operator and is undesirable to the aircraft designer. The intimate relationship of fuel management schemes and aircraft efficiency is not known to many outside the airline/airframe industry. A brief review of this relationship is brought into this report to better define the alternatives available in applying other data in this report to improving the cold fuel supply situation.

The way fuel is held, transferred, and used in an aircraft is known as its fuel management schedule. Specific components or fuel subsystems may be installed to accomplish this task. The combination of the fuel management schedule and the fuel tankage arrangement of an aircraft has a very significant effect on the minimum fuel temperature experienced on a given flight.

Study of various aircraft will show that there are many different fuel management systems in use. Fuel management can be quite complicated on a large multi-engine aircraft and may vary with aircraft model and with specific missions. Generally, fuel management schemes have been driven by requirements for center-of-gravity (CG) control and structural load control with the ultimate goal of having a more productive airplane design.

Aircraft CG shift can be controlled by moving fuel among the tanks or by using fuel from the tanks to the engines in a prescribed manner. These fuel management techniques may be applied during aircraft loading to either allow more variation in where payload can be placed aboard the aircraft or to accommodate specific cargo loadings where weight may be concentrated at a specific location.

Structural load control is usually practiced by maintaining fuel outboard in the wings to counter aerodynamic loads. Load alleviation using counteracting fuel load forces results in a lighter airframe structural requirement than if

the aerodynamic loads were handled by pure structural strength. Wing flutter damping by maintaining fuel mass outboard also results in reduced structural weight of the airframe. Reduced airframe weight can allow greater payloads or can give greater fuel efficiency to the airplane.

Combinations of CG control and structural load control can be used in other ways to reduce airplane weight and drag. These concepts are "built in" to the basic airplane design to make it the most efficient package possible.

Deviations from normal fuel management schedules to maintain fuel temperatures at higher levels would have to be evaluated for each specific aircraft to determine what penalties may result. If the deviations were frequent, they could result in greater fuel consumption which would be counterproductive to the original intent of increasing fuel availability and reducing costs by fuel freezing point increases.

Future design/procurement requests for specific aircraft should include studies to evaluate the trade-offs involved in designing the vehicle to accommodate fuel of an increased freezing point. These studies would include alternative fuel management concepts.

Fuel Tank Insulation and Heating

There are many alternatives which may be used to improve the ability to operate aircraft with fuels of higher than traditional freezing points. Some schemes are being studied and tested which affect the design of the aircraft and its systems.

Fuel tank insulation would reduce the fuel cooling rate and may ameliorate the effects of low atmospheric temperature transients. The application of insulation to the outside of a wing surface will affect the drag of the airfoil. Internal insulation is very difficult because of the complexity of internal structure. The available fuel volume would be reduced. Spraying of foam-in-place insulation would cover the internal structure and hinder the very important procedures of structural inspections and corrosion control.

Tank fuel heating schemes abound and have significant possibilities of replacing currently employed cooling methods. If a currently installed cooling system can be replaced or modified, the penalty of added equipment can be reduced. Fuel temperatures and systems have upper limits; so the hot day cooling case must be a part of every evaluation of suggestions for using fuel as a heat sink.

NASA CR-159568 evaluated five concepts for tank fuel heating (1). Design and Evaluation of Aircraft Heat Source Systems for use with High-Freezing Point Fuels, A. J. Pasion, NASA CR-159568, May 1979. Two concepts were selected from five candidates for further evaluation. These used either engine oil heat or an engine-driven electrical generator to furnishing energy for fuel tank heating. A NASA contract has been let to Lockheed California Company to experimentally examine the selected heating systems and to assess their effect on fuel recovery from a simulated wing tank.

(1) Design and Evaluation of Aircraft Heat Source Systems for use with High-Freezing Point Fuels, A. J. Pasion, NASA CR-159568, May 1979.

There are fundamental considerations to be kept in mind on any design change. These include safety, complexity, reliability, operating and maintenance costs, design and installation costs, fuel consumption, weight, etc. Safety will not be compromised, so the final consideration in any evaluation will be the economic benefits versus the economic penalties. The manufacturing costs, the installation costs, and the operating costs not affected by fuel price can be readily evaluated. There is a definite need to establish the fuel price effects of any fuel freezing point specification change in order that decisions can be made on design changes.

Fuel Temperature Measurements

All aircraft have a consideration of fuel temperature in their design and in their operating instructions. Some aircraft have no direct temperature measurement, but rely on the use of air temperature limits to control fuel temperatures. Where direct fuel temperature measurement is provided the system is based on considerations of both high & low fuel temperature limits, fuel system design, fuel management procedures, accessibility for production and maintenance, system precision, system reliability (simplicity), cost effectiveness, and anticipated aircraft operations.

The typical aircraft fuel temperature indicating system is made up of one thermistor type sensing element and one cockpit mounted indicator. The sensing element is the varying resistance in a Wheatstone bridge circuit with all the electronics contained in the indicator housing. Cockpit display panel space has been a limiting factor so if more than two locations were to be displayed a switch was used to select the desired circuit. Future designs will have similar circuitry, but the signal will be microprocessed and fed into an on board computer. The information will be displayed digitally to the flight crew on a color screen at their command.

The fuel tank temperature probe is usually mounted so as to be bathed in fuel during the desired period of flight. This means that it is probably in a main fuel tank. The probe will likely penetrate either the front or rear tank boundary at mid-height due to structural strength considerations. The penetration into the fuel will vary and may be determined by a desire to use a common temperature sensor in the fuel system, the hydraulic system and the oil system.

The coldest or warmest fuel may be at locations other than where the probe is located. There are tolerances on all the parts of the system that must be considered as well as fuel temperature gradients. The properties of the fuel and the accuracy of test methods for determining these properties must be considered.

After all of the variables are taken into account the manufacturer establishes a margin relative to the measured freeze point of the fuel which should be maintained at the cockpit indicator to ensure satisfactory system performance. These margins can be expected to vary among the many airplanes in use due to their design differences. Traditionally fuel freeze points were so low that no fuel temperature limit encounters occurred and fuel temperature monitoring received little attention. The desire for unrestricted availability of aviation turbine fuel and the resulting pressure to raise allowable fuel freeze points will require increased attention to the details of fuel temperature measurement system requirements and use.

A P P E N D I X   B

RELATION OF FUEL COMPOSITION
TO LABORATORY AND SIMULATOR TESTS

RELATION OF FUEL COMPOSITION TO LABORATORY AND SIMULATOR TESTS

The wax which forms in a fuel at low temperature is composed of normal paraffins. Since the n-alkane composition of eight of the test fuels had been determined by gas chromatographic analysis as shown in Table B-I, it seemed desirable to relate these data on composition to the results of various laboratory tests and to the Solidification Index which was shown in the report to correlate with holdup in tank simulator tests. The test data on the eight fuels are shown in report Table V.

There is a strong relationship between S.I. and each of the other low temperature tests as shown by Figure 8 for these eight fuels. As the report points out, other tests besides Freezing and Pour Points might have been used to develop the correlation with holdup, but, for initial correlation studies, Freezing and Pour Points seemed like reasonable approximations of the extremes of 0 and 100% holdup respectively.

Each of the low temperature tests also represents some degree of precipitated wax in liquid fuel. By definition, the Freezing Point represents a liquid fuel at the melting point of the last wax crystal. For the other tests, the amount of wax present at the designated end point is unknown. One way of estimating this amount of wax is to relate the cumulative percentage of n-alkanes in each fuel, starting with the highest molecular weight, to each test result. A computer study was undertaken to develop these relationships for each test as well as the Solidification Index of holdup itself.

Freezing (Melting) Point of pure n-alkanes

The melting point of individual normal paraffins is far higher than the freezing (i.e. melting) point observed for a fuel containing a mixture of n-alkanes (as well as other types of hydrocarbons) due to eutectic effects. Figure B-1 is a plot of individual n-alkane melting points against carbon number. On this same plot the freezing point of the eight test fuels are also shown, the horizontal lines cover the range of carbon numbers of the three highest molecular weight n-alkanes detected in each fuel. Petrovic and Vitorovic have published a method for estimating the freezing point of jet fuels based on the last three members of the n-alkanes detected in fuel (1).

(1) K. Petrovic and D. Vitorovic "A New Method for the Estimation of the Freezing Point of Jet Fuels Based on Their n-Paraffin Content" J.I.P., Vol.59 No. 565, Jan. 1973.

For the jet fuels (numbered 1, 8 & 9), there appears to be a minimum temperature difference of almost 60-70°C between the highest n-alkane melting points and observed freezing points. For the heavier diesel fuels, the minimum temperature difference to the freezing point is less. This trend suggests that the molecular weights and amounts of the highest carbon number n-alkanes may correlate with freezing point and with the other low temperature tests where wax is present to some extent as a temperature end point lower than the freezing point is observed.

Computer Model for Relating n-alkanes to Low Temperature Tests

Preliminary plots of cumulative percent n-alkanes starting with the highest carbon number against S.I. suggested that a good correlation would exist at relatively low levels such as 2%. The computer was then instructed to make a linear interpolation for one, two and three percent n-alkanes starting with the highest carbon-number (Table B-1) for each fuel. Regressions between these different percent wax levels and the various test temperatures reported in Table B-II were computed. The significant results with R^2 greater than 0.95 and f greater than 100 are summarized in Table B-III.

The best correlation was found between the Enjay Fluidity Test and the two percent level. However, other tests showed good correlations also. The best values are underlined in Table B-III and can be summarized as follows:

	% n-alkanes		
Test	One	Two	Three
Freezing Point	X		
Pour Point			X
Cold Filter Plugging Point	X		
Enjay Fluidity		X	
Seta Detector	X		
Shell Cold Flow			X
S.I. =		X	

Figure B-2 is a computer plot of the residual error between actual Freezing Point and the Freezing Point predicted from the one percent n-alkane level. Except for LFP-7 the error was within 2.5°C (The Petrovic correlation standard error for jet fuels only is 0.6°C.)

Figure B-3 is the computer plot of the Seta Point Detector residual error in prediction at one percent n-alkane. It appears to be as good or better than Freezing Point.

Figure B-4 is the computer plot of Enjay Fluidity Test residual error at the two percent n-alkane level. All values are within 2°C. For comparison Fig. B-5 is the computer plot of Solidification Index residual error at the two percent n-alkane level. The maximum error is about 4°C.

The different percent n-alkanes which proved to have the best correlation coefficients with each test can be translated into the lowest carbon number (or the lowest molecular weight n-paraffin) associated with each amount of wax. When this lowest carbon number for each fuel is regressed against the temperature reported for each test, the equations in Table B-IV result. these equations are plotted in Figure B-7 to illustrate how one could estimate Freezing Point, Solidification Index or any other test from the composition of the wax. That composition is estimated by the technique illustrated in Table B-IV.

DISCUSSION

The one percent correlation with Freezing Point seems very reasonable since the definition of the temperature at end point is consistent with wax content approaching zero. By the same token, the Seta Point Detector was designed to attempt to match the freezing point, i.e. minimum wax. The wax to plug the filter of the Cold Filter Plugging Test also appears to be present in small quantity.

The three percent correlation with Pour Point and the Shell Cold Flow Test is interesting since each test involves holdup of liquid fuel by a wax matrix at the critical temperature. Since S.I. is an approximate average of Freezing and Pour Points, good correlation of S.I. at two percent is to be expected. The Enjay Fluidity Test with its excellent correlation at the 2% level may prove to be as good as S.I. in correlating with actual holdup in simulator tanks.

Knowledge of the n-alkane content makes it possible to estimate the composition of the precipitated wax in terms of the limiting (or average) carbon number (i.e. molecular weight) for a specific level of precipitation. For this study the technique for estimating composition is based on fractions added to the C_{21} n-paraffin which is the highest n-alkane found in the test fuels. Based on this technique applied to eight test fuels, it is possible to use the appropriate equations or graphs to predict not only fuel Freezing Point and Solidification Index but also other low temperature test results, which involve a mixture of wax crystals in liquid fuel. It is unfortunate that compositional data are available on only eight fuels because a larger body of data might make it possible to optimize this method for utilizing fuel analysis with respect to each of the low temperature tests.

The methods discussed in this Appendix were not applied to fuels containing a flow improver. The effects of flow improver on these correlations is not known.

SUMMARY STATEMENTS

- The n-alkane content of fuels can be used to estimate the Freezing Point of fuels in confirmation of the Petrovic and Vitorovic correlation, and also to predict the results of other low temperature tests.

- The concept of using a low but fixed cumulative percent of the highest molecular weight n-alkanes in fuel to predict the wax present in two-phase tests such as CFPP, Enjay Fluidity, Shell Cold Flow, Setapoint Detector, etc. appears to be supported by the high correlation coefficients obtained.

- For any given level of precipitated wax, it is possible to estimate wax composition and from this estimate to approximate the corresponding temperature of any of the low temperature tests.

- Solidification Index shows a high correlation coefficient with two percent n-alkanes. The Enjay Fluidity Test also correlates well with two percent n-alkanes and should be investigated further for use in analyzing holdup of wax in simulator tanks.

- Although this computer study has perforce been limited to eight test fuels, the concept of applying GC analysis for n-alkanes to predict low temperature laboratory and bench tests should be expanded.

TABLE B-1

n-Alkanes in Jet Fuels*

n-Alkane	LFP-1 Jet A	LFP-3 Distillate (Paraffinic)	LFP-4 Distillate (Naphthenic)	LFP-5 Intermediate (Paraffinic)	LFP-6 Intermediate (Naphthenic)	LFP-7 Distillate (Paraffinic)	LFP-9 Jet A	LFP-8 Jet A-1
C-7								0.29
C-8	.58	.01	.01	.08	.08	.21	.16	0.28
C-9	1.62	.24	.05	.22	.15	.47	.86	0.42
C-10	3.08	.57	.18	.56	.32	1.02	2.58	0.76
C-11	4.61	1.06	1.14	1.07	.56	1.51	4.49	2.26
C-12	5.78	1.64	.98	1.91	.93	1.70	5.16	2.39
C-13	5.41	2.36	1.07	2.47	1.77	2.35	4.23	1.88
C-14	2.82	2.76	.85	2.31	2.37	2.89	2.07	1.45
C-15	1.19	2.93	.89	2.42	2.80	3.01	.70	0.53
C-16	.51	2.37	.87	1.51	1.83	2.35	.20	0.12
C-17	.27	1.95	.86	.82	1.06	1.81	.07	0.02
C-18	.16	1.32	.73	.38	.37	1.11	.04	0.01
C-19	< .01	.77	.57	.13	.09	.64	< .01	
C-20	< .01	.31	.37	.06	.09	.33	< .01	
C-21	-	-	.19	-	-	.16	-	
Total	26.03	18.38	8.76	13.94	12.42	19.56	20.56	10.43

* - Analytical precision was ± 5.6 percent.

TABLE B-II

SUMMARY OF LOW TEMPERATURE TEST RESULTS
(AVERAGE VALUES IN -°C)

Test	LFP-1	LFP-3	LFP-4	LFP-5	LFP-6	LFP-7	LFP-9	LFP-8
F (Freeze Pt.)	-41	-17	-14	-28	-28	-10	-46	-52
P (Pour Pt.)	-46	-25	-30	-33	-35	-16	-48	-53
C (CFPP) Cold Flow Plugging Point	-47	-22	-16	-32	-34	-16	-52	--
E (Enjay Fluidity)	-40	-18	-20	-29	-29	-16	-43	--
D (Seta Point Detector)	-42	-19	-18	-30	-30	-15	-46	--
S (Shell Cold Flow)	-43	-15	-24	-30	-30	-15	-45	--
SI (Solidification Index)	-44.2	-21.5	-22.7	-31.0	-32.1	-13.3	-47.7	-53.2

TABLE B-III

CORRELATION COEFFICIENTS OF VARIOUS N-ALKANE CONTENTS WITH LOW TEMPERATURE LAB TESTS

(8 TEST FUELS, LFP-1 TO LFP-9)

		Basis for Cumulative n-alkanes (Starting with highest carbon No.)		
Laboratory Test	Code	1%	2%	3%
Freezing Point	F	0.992	0.987	0.971
Pour Point	P	0.947	0.962	0.970
Cold Filter Plug Pt.	C	0.989	0.973	0.936
Enjay Fluidity	E	0.990	0.996	0.982
Seta Detector	D	0.993	0.990	0.967
Shell Cold Flow	S	0.958	0.984	0.993
Solidification Index		0.978	0.983	0.978

TABLE B-IV

TEST TEMPERATURE VS. CARBON NUMBER OF WAX PRECIPITATE

(Equations Relating Different Test Temperatures, °C, To Lowest N-alkane At Different Levels)

F = -8.34 (C_n at one percent) + 9.71
P = -7.77 (C_n at three percent) + 12.38
C = -8.52 (C_n at one percent) + 5.71
E = -7.10 (C_n at two percent) + 9.29
D = -7.19 (C_n at one percent) + 2.67
S = -8.72 (C_n at three percent) + 22.37
SI = -8.24 (C_n at two percent) + 12.75

To calculate (C_n at x percent), add weight percent n-alkanes starting with C_{21} until a limiting C_i is reached. For example, LFP-1 at 1%:

n-alkane	wt.%	cum. %	ΔC_n
C_{21}	0	0	1
C_{20}	.01	.01	2
C_{19}	.01	.02	3
C_{18}	.16	.18	4
C_{17}	.27	.45	5
C_{16}	.51	.96	6
C_{15}	1.19	1.0*	6.04*

* Includes portion of C_{15}

$\therefore$ C_n at one percent is $C_{(21 - 6.04)} = C_{14.96}$

FIGURE B-1

FREEZING (MELTING) POINT OF N-ALKANES
(FREEZING POINT OF TEST FUELS PLOTTED AGAINST
HIGHEST N-ALKANES DETECTED BY GC ANALYSIS)

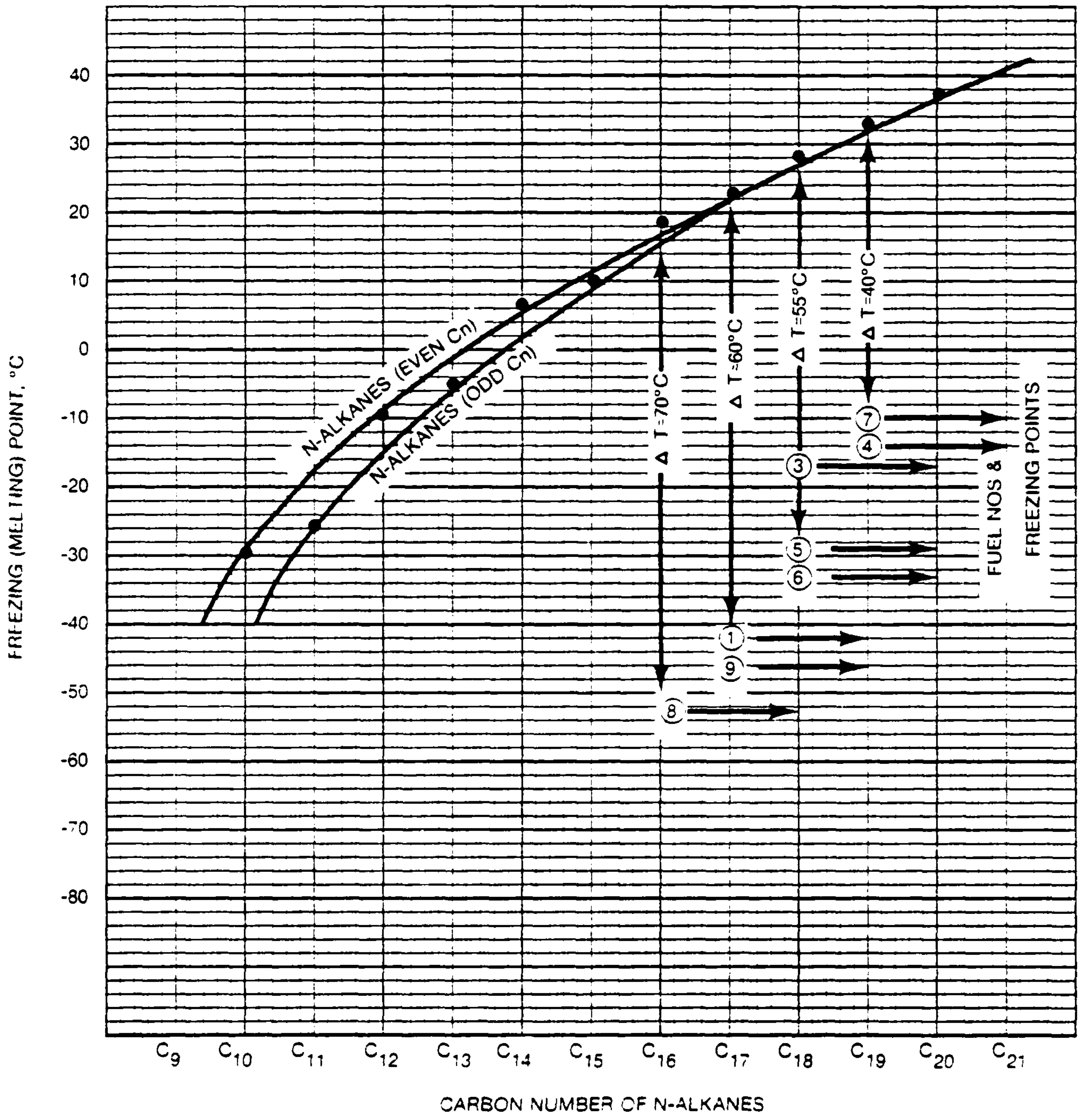


FIGURE B-[illegible]

RESIDUAL ERROR ([illegible]) IN PREDICTING FREEZING POINT FROM [illegible] CUMULATIVE n-ALKANES

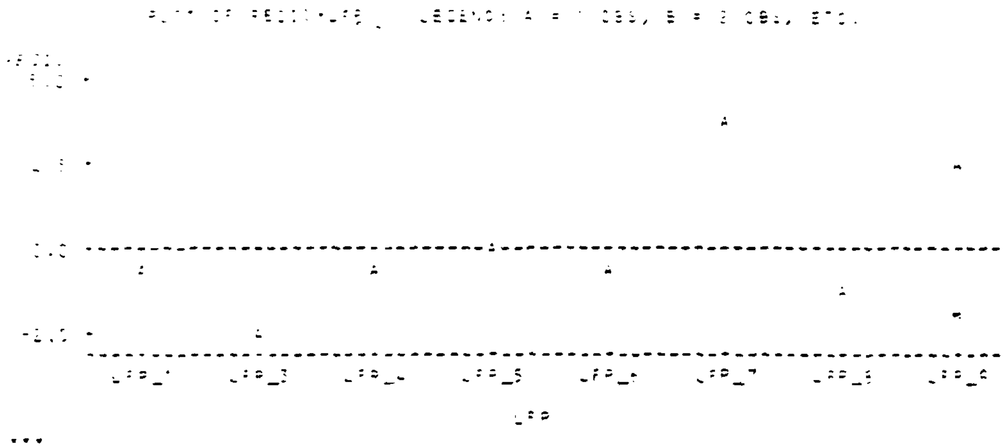


FIGURE B-[illegible]

RESIDUAL ERROR ([illegible]) IN PREDICTING CETAPOINT FLOW FROM [illegible] CUMULATIVE n-ALKANES

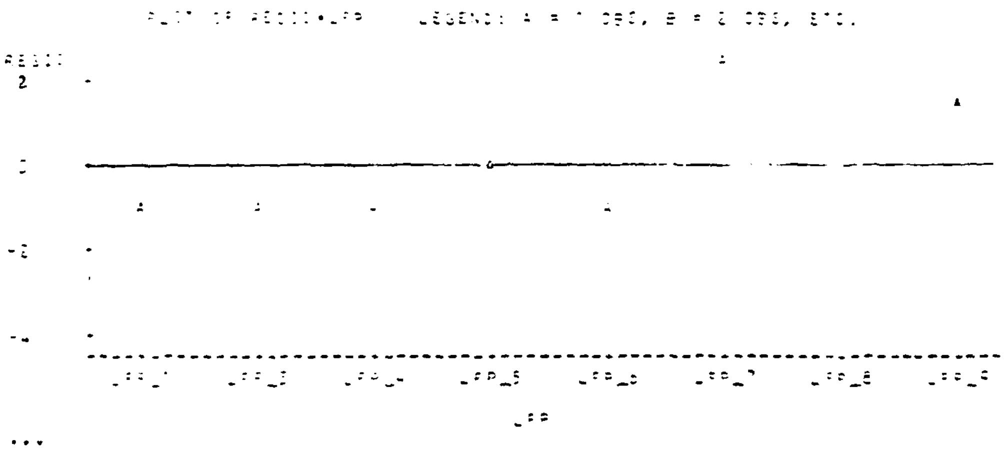


FIGURE B-4

RESIDUAL ERROR (°C) IN PREDICTING ENJAY FLUIDITY POINT FROM 2% CUMULATIVE N-ALKANE

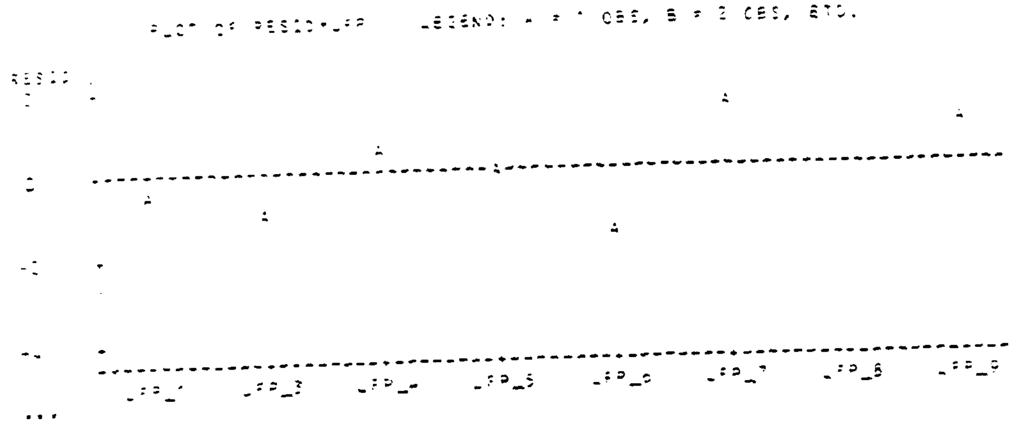


FIGURE B-5

RESIDUAL ERROR (°C) IN PREDICTING SOLIDIFICATION INDEX FROM 2% CUMULATIVE N-ALKANE

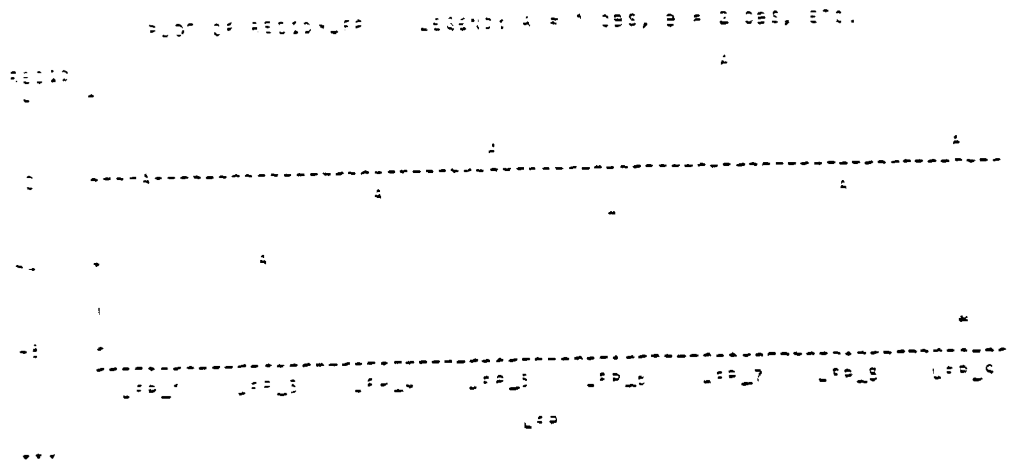
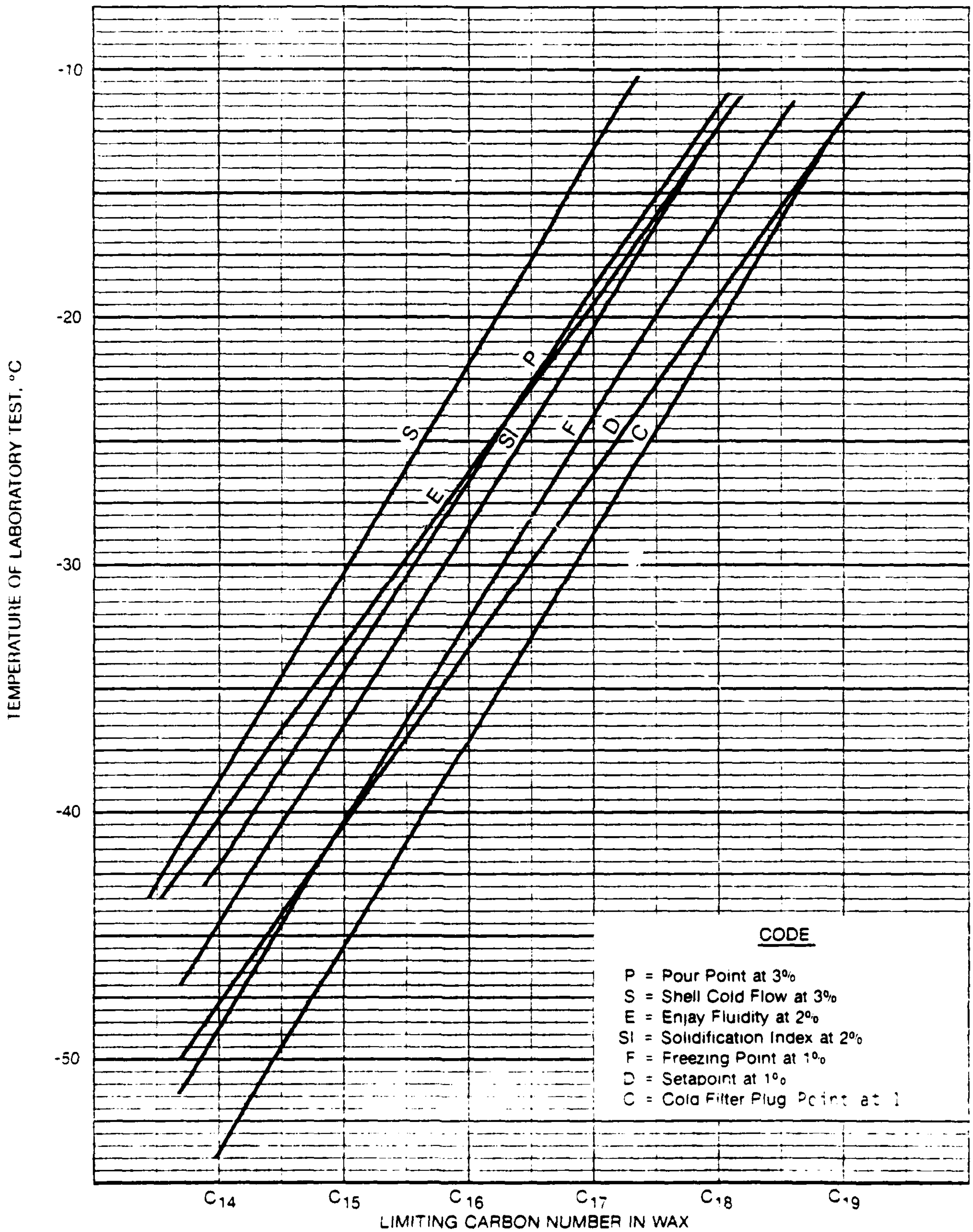


FIGURE B-6

TEST TEMPERATURE VS. ESTIMATED CARBON NO. OF WAX PREC.



A P P E N D I X   C

LOW TEMPERATURE MEASUREMENT METHODS

LOW TEMPERATURE MEASUREMENT METHODS

The fuel low temperature test methods described below involve either one or two phases, i.e., a mixture of suspended wax in fluid, at the time a measurement is made. The presence of either one or two phases is noted in the description of each test. Remarks on holdup refer to the apparatus peculiar to the test method.

Freezing Point (ASTM D 2386)

While being stirred, 25 cm^3 of fuel is cooled in a special test tube to the temperature at which wax crystals appear. It is then allowed to warm slowly until the wax crystals disappear completely. The temperature of wax disappearance is the freezing point. (Freezing point is reported to the nearest 0.5°C.)

Freezing point by this definition is equivalent to a single liquid phase and therefore zero holdup if all of the fuel was at a temperature equal to or greater than this temperature.

Pour Point (ASTM D 97)

As 163 cm^3 of unstirred fuel is cooled in a special test tube, it is checked at 5°F (3°C) intervals to see whether the liquid level moves in response to tilting the test tube. The lowest temperature at which movement is noted is the pour point. (Pour point is reported to the nearest 5°F or 3°C.)

At the pour point two phase conditions exist, a liquid phase trapped in a wax matrix. It could correspond to maximum holdup.

Cloud Point (ASTM D 2500)

As unstirred fuel is cooled in a pour point tube, it is checked every 2°F (1°C) for the appearance of a wax cloud or haze. The cloud point is the temperature at which the wax haze first becomes noticeable. (Cloud point is reported to the nearest 2°F or 1°C.)

Cloud point represents the first appearance of a second phase. It could correspond to a very low degree of holdup.

Note: Although none of the above three tests specify the rate of cooling in degrees per hour, the cooling rate is controlled in each test by using constant temperature baths at specified temperatures and by closely delineating the testing apparatus and sample volume.

Shell Cloud/Pour Analyzer

This is an automatic instrument that measures the thermal crystal point (TXP) or temperature at which wax is initially separated during controlled cooling. This temperature is detected by thermal analysis. The instrument also measures as a solid point (TSP) by a falling-ball technique. Experience has indicated that the TXP and TSP predict cloud and pour point, respectively.

Shell Cold Flow Test

The tester is comprised of two fuel compartments, separated by a poppet valve. A measured volume of fuel is placed in the upper compartment of the tester and cooled to the test temperature. The poppet valve is then opened for a fixed time, and the amount of fuel drained to the lower compartment measured. The test is repeated at different test temperatures to establish the minimum temperature at which all fuel will drain from the top to bottom compartments of the tester. Complete test details are given in the Journal of the Institute of Petroleum, November 1962. (See Figure 9 and discussion in the section on Effect of Repeated Freezing of Fuel Specimens in main text.)

Cold Filter Plugging Point Test (CFPP) (Institute of Petroleum - IP 309)

The test sample (45 cm^3) is cooled at a rate of 40°C per hour to the desired test temperature. At intervals of 1°C, a vacuum of 200 mm water gauge is applied to draw the fuel through a 45-micron wire mesh filter. The CFPP is defined as the highest temperature at which the fuel will not flow through the filter or require more than 60 seconds for passage of 20 cm^3 of fuel.

CFPP is a measure of the wax present in a two-phase flow system. It might correspond to an intermediate level of holdup.

The Enjay Fluidity Test (EFT)

The fluidity tester consists of two graduated transparent-plastic cylinders (3.8 mm in diameter) which are screwed together to form two compartments with an interconnecting brass capillary (2.54 mm in diameter). A fuel sample of 40 ml is placed in the lower compartment and cooled in a cold temperature bath at 4°F per hour to the test temperature. The tester is inverted and the volume of fuel recovered in the lower compartment after three minutes is measured. This procedure is repeated at several test temperatures to determine the temperature at which 80 vol % is recovered in the lower compartment.

EFT temperature implies about 20% holdup in this device.

Setapoint Detector

This instrument is designed to predict the freezing point of aviation turbine fuel. About 6 ml of fuel is contained in a sample chamber bored into the center of an aluminum block with an illuminated viewing window. The fuel is circulated at 1 ml per second at 10 mm Hg pressure through a 400-mesh (33 microns), stainless steel filter. The aluminum block temperature is controlled by compressor refrigeration and thermoelectric cooling. The temperature at which either the filter plugs, NO FLOW point, or at which flow resumes on heating, FLOW point, can be used to define low temperature behavior. The FLOW point has been correlated with ASTM D2386/IP16 freeze point.

Setapoint is a measure of the wax present in a two phase flow system. It might correspond to either low or intermediate holdups.

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